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Preliminary Design Options for Meteor Burst Communications Systems Buoy Relays

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This report contains an analysis and evaluation of design options associated with developing a Meteor Burst Communications Systems (MBCS) buoy relay, including antennas and power supplies, that meet various operational requirements.

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EXECUTIVE SUMMARY

1.0 INTRODUCTION

Unique features of Meteor Burst Communications Systems (MBCS) that make them desirable for some operational requirements include

1. the relative covertness of the MBCS link;

2. the survivability/rapid recovery of the associated VHF propagation path after high altitude nuclear explosions. The limiting 1100 nautical mile range of a MBCS link can be increased by relaying messages.

This report contains an analysis and evaluation of design options associated with developing a MBCS buoy relay, including antennas and power supplies, that meet various operational requirements.

2.0 APPLICATIONS FOR MBCS BUOY RELAY

Applications for which a MBCS buoy relay can be useful include those involving relatively low volume communications or data exchange between fixed land sites, submarines, surface ships, aircraft, missiles and rockets. Tables ES.1 summarizes several features of a MBCS buoy relay for several applications.

Table ES.1. Types of operational requirements satisfied by MBCS buoy relay.

Section No.	Type of Requirements (Relay/Service)	Terminals Served		Buoy Relay			
		Type	Covert	Covert	Operating Mode	Transmit Duty Cycle	Average Power (watts)
2.1	Trans Ocean Relay	Shore/Ship	No	Yes	Remote	20 Msg/hr	0.9
	Trans Ocean Relay	Shore/Ship	No	Yes	Remote	12% of time	75
2.2.1	Report back of data	Sub /Ship	Yes	No	Master	33% Msg	207/Msg
2.2.2	EAM delivery	Sub	Yes	No	Broadcast	100% Msg	620/Msg
2.3	Buoy Relay Network	Shore/Ship	Yes	No	Remote/Master	16%/Msg	103/Msg

NOTES:

1. The "Section No." identifies where the requirement is discussed in greater detail.
2. Identifying a terminal as covert means it will transmit only short bursts and does not operate as a master station.
3. The average power requirement is necessary for buoy design. Larger buoys are required for greater power demands.

3.0 ANTENNA

3.1 General Types

Antenna types possibly suited for use on a buoy include (see figure 3.1 for sketches)

P vertical halfwave element (e.g., dipole, J-antenna);

P vertical collinear dipole array;

P crossed horizontal dipoles;
stacked cross horizontal dipoles;

P multi-element beam (Yagi-Uda antenna, log-periodic, etc.)
loops(s) (vertical or horizontal);
sleeve monopole
modified ground-plane antenna

Each of these antennas has been considered for applicability to MBCS buoy relays.

3.2 Gain Pattern

Four of the generic antenna types (marked by a "P" in the above list) have been evaluated in detail, including computing their radiation patterns for various heights above the sea. The results indicate

1. vertically polarized antennas have optimum gain, especially for low elevation angle radiation, when they are mounted at lower heights, i.e., 10 feet;

2. horizontally polarized antennas have better gain at lower elevation angles when mounted at higher heights, i.e., 40 feet.

4.0 MBCS PERFORMANCE VS ANTENNA CHARACTERISTICS

The MBCS link performance is affected by how well the antennas illuminate or see meteor trails in the meteor region between the two terminals. Optimum performance is achieved when the antenna provides maximum gain in the meteor regions where the greatest number of meteors occur.

Calculations have been made of MBCS message waiting time (time between initiation of a message transfer and its arrival at the destination) for various candidate antennas using the computerized model developed by Haakinson[24] at the U.S. Dept. of Commerce.

Some results are shown in the following figure. The vertically polarized dipole at 10 feet height provides performance about as good as, or superior to, that provided by the higher (and therefore more cumbersome) vertical collinear dipole array or the horizontal crossed dipole array.

Therefore, a vertically polarized antenna at low height on the buoy is recommended unless MBCS networks to be used by the relay are already implemented with horizontally polarized antennas. The same polarizations must be used on each end of a link.

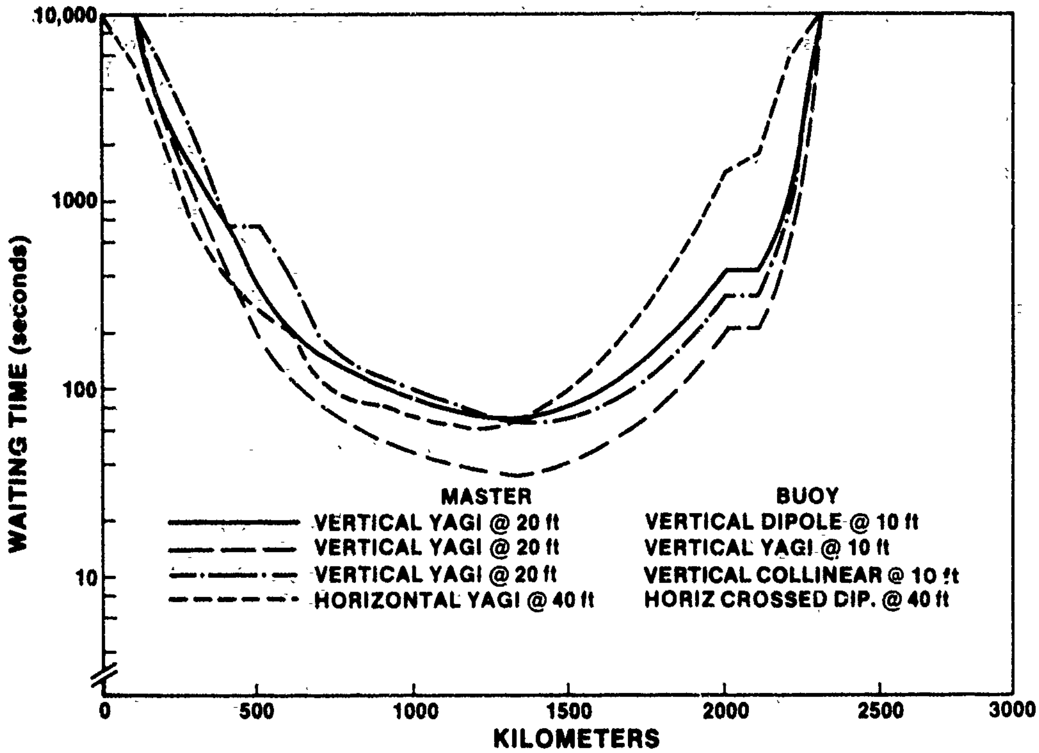


Figure ES.1. Computed MBCS message waiting time vs link distance for various vertically and horizontally polarized antennas at their optimum operating heights for 50 MHz.

5.0 POWER SOURCES

A broad survey was made of known power sources that could satisfy (for up to 3 months) the power requirement summarized in the preceding table. The survey addressed:

1. power sources that are available as off-the-shelf products or only require engineering for a specific application,

2. feasible power sources under development that offer significant advantages over currently available sources in terms of endurance, energy density, cost savings, or ease of deployment.

Listings by category of these sources are included in appendix A, and descriptions of them are included in appendices B and C.

A listing of the most promising candidates are included in table ES.2. It indicates the recommended selections based on minimal cost for each mission listed and those selections based on minimal size and weight for each mission.

Table ES.2. Summary of selected power source candidates.

MISSION	1	2	3	
Receiver/Processor	0.7 W	0.7 W	0.7 W	
Peak Transmitter Demand	620 W	620 W	620 W	
Average Power	1 W	100 W	300 W	
Duration Energy	90 Days	90 Days	90 Days	
Energy	2160 WH	216 kWh	648 kWh	
WEIGHT/VOLUME/COSTS	($lbs/ft^3/\$k$)	($lbs/ft^3/\$k$)	($lbs/ft^3/\$k$)	REMARKS
PRESENT TECHNOLOGY				
Alkaline Cells	62/.58/0.14[1]	6200/58/14	18,500/175/41	Lowest risk
Lithium Cells	11/.13/0.4[2]	1100/13/40[2]	3300/40/120[2]	Safety restrictions
Zinc Air Cells	50/.50/0.2	2700/37/4[1]	8100/110/12[1]	Nicad required, air intake
Gas Fired Thermoelectric Generators	NA	1500/40/8	5000/110/20	Nicad required, propane storage, air and exhaust ports
ADVANCED TECHNOLOGY				
Diesel Fired Thermoelectric Generators	NA	1900/40/10	6500/140/23	Nicad required, diesel storage, air and exhaust, \$.5 M R&D required
Alum Air Fuel Cells	NA	1100/40/10	2000/90/18	\$2 M R&D required air intake
Gas Fired Turbine Generators	NA	370/25/20	800/30/25[2]	\$1 M R& D required, Nicad required, air and exhaust, propane storage
Sea Water	0/.10/0.5[1,2]	500/10/3[1,2]	1500/30/10[1]	\$.5 MM R&D required, Nicad required, large area cathode

NOTES:

1. Recommended selections based on minimal cost.
2. Recommended selection based on minimal size and weight.

6.0 BUOY SYSTEM DESIGN

Selection of a buoy to support the MBCS station depends upon several factors, including:

1. environmental conditions,
2. station keeping requirements,
3. antenna requirements,
4. energy source requirements,
5. deployment/repair/recovery considerations, and
6. navigation/position location requirements.

In particular, the buoy must maintain a near vertical orientation while supporting the power source and communications equipment necessary for a given mission.

Several classes of buoys are reviewed with respect to their suitability for MBCS applications, including surface-slope following buoys (figure 6.3), spar buoys (figures 6.4-6.6), and pendulous surface riding buoys (figures 6.7 and 6.8). For applications requiring relatively small payloads, a pendulous spherical buoy is recommended due to its favorable stability characteristics and reserve buoyancy. For the larger master stations, a combination boat/pendulum buoy is recommended. In addition to possessing the advantages of the pendulous spherical buoy, the boat/pendulum buoy has improved access to internal compartments, withstands greater currents and heaving motions, and may be towed to position. Three preferred designs utilizing pendulous buoys that span a range of mission applications are specified in section 6.5 of the report.

For some MBCS applications, relatively inexpensive and expendable drifting stations may be suitable. Where station keeping is required, buoys may be passively restrained with drogues or anchors, or actively propelled.

7.0 MBCS BUOY STATION SURVIVABILITY

Station survivability is a function of environmental factors (such as water depth and the severity of storms) and human factors (such as peacetime intrusion or wartime jamming or destruction). MBCS station life might be prolonged by using pop-up or piggy-back stations or last-minute deployments.

8.0 CONCLUSIONS

The feasibility of operating MBCS relay buoys for various types of operational missions has been examined. The type of buoy mounted antenna best suited for this application is vertically polarized, primarily because it performs well at low heights. Table ES.3 summarizes design characteristics of possible power supplies and buoys for several applications.

Table ES.3. MBCS buoy relay designs summary.

Type	Power Supply		Buoy Design		
	Type	90 Day Energy	Type	Storage Size	Weight (lb)
Remote	Lithium Battery	2.2 kWh	Deployable Pendulous	8″ x 8″ x 4′	200
Master/Remote	Zn-Air Battery	216 kWh	Pendulum/Spherical	5′ x 5′ x 12′	5,000
Master	Zn-Air Battery	648 kW	Boat/Pendulum	6′ x 6′ x 30′	10,000

MBCS BUOY RELAY

1.0 INTRODUCTION

Meteor Burst Communications Systems (MBCS) have several unique features that make it particularly desirable for satisfying some types of communications requirements. Two of the more significant features are (1) the covertness of particularly the "remote" terminal of a MBCS and (2) the relative survivability of the VHF propagation medium in high altitude nuclear explosion disturbed environments.

Other characteristics limit MBCS utility. These include a maximum range of only about 1100 nautical miles, and an intermittent communications link limited to only a few percent duty cycle due to the intermittent nature of VHF meteor trail reflections.

The 1100 nautical mile range of MBCS can be mitigated by incorporating relays between the communications sites to be served. For example, a test communications link was established between Lewes, DE, and Jacksonville, FL, using a relay operated at Bermuda and aboard a balloon (reference 1) at an altitude of 70,000 feet.

Applications for which a MBCS buoy relay can be useful include those involving relatively low volume communications or data exchange between fixed land sites, submarines, surface ships, aircraft, and missiles and rockets operating near, on, or across the oceans of the world in which one end of the link needs to be relatively covert. Also, survivability in a nuclear environment makes MBCS useful for the trans- and post-attack phases of nuclear war.

The objectives of this report are to describe operational features and present an evaluation of various design options associated with implementing MBCS buoy relays.

A brief general summary of MBCS is presented in section 1, DoD applications and the associated operating duty cycle of buoy systems are discussed in section 2, and antenna design and its effect on link performance is presented in sections 3 and 4. Results of a survey of power sources suitable for buoy systems is in section 5, and the design of the buoy itself is discussed in section 6. Buoy systems survivability and conclusions are discussed in sections 7 and 8.

1.1 DESCRIPTION OF MBCS

When meteors are vaporized through impact with the atmosphere, long trails are formed at altitudes of 85 to 115 km. These trails are cylinders of ionization, tens of kilometers in length, with a radius a thousand times smaller, and can function as high-altitude reflectors of very high-frequency (VHF) radio transmissions from the ground. Of the total of about 10^{20} meteors entering the atmosphere each day, about 10^{12} have a mass large enough to produce effective reflecting trails. Each hour, several hundred such trails are positioned and aligned properly to allow specular reflection of a VHF signal between two given geographical locations. A channel of communication can thus be formed. The channel is short-lived (up to 10 seconds with a medium value of about 0.3 second) because of trail dissipation. It provides a maximum range of about 1100 nautical miles (2000 km) because of the 85- to 115-km height of the meteor trail region and the curvature of the earth. This is illustrated in figure 1.1. The name "Meteor Burst Communications System" (MBCS) derives from the brevity of the transmissions.

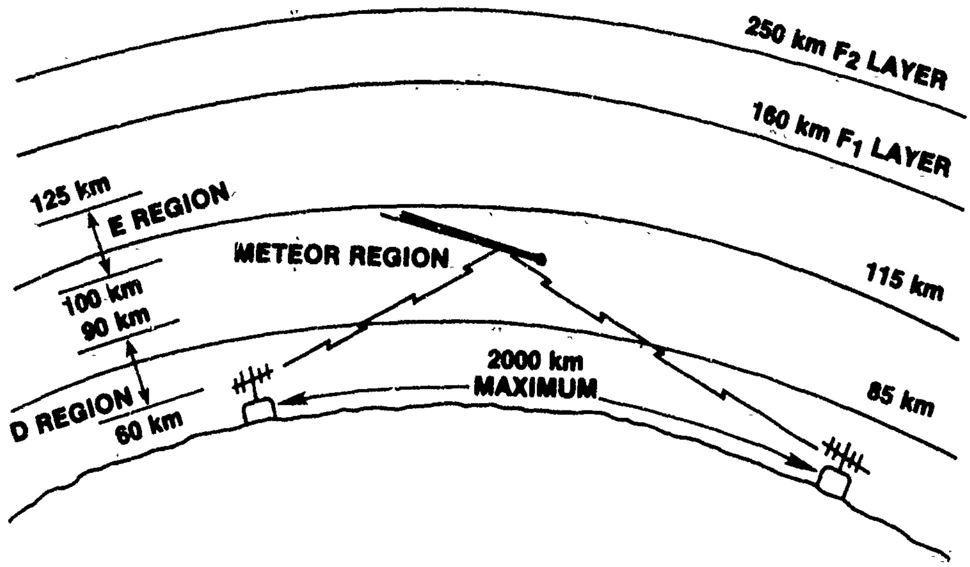


Figure 1.1. Diagram of a MBCS link illustrating the height of the meteor region within the ionosphere and the maximum range of communications associated with it.

In the normal operation of a MBCS, a master station continuously transmits a probing signal. When a called station (or a "remote" station) receives this signal, it immediately answers the master station via the same reflecting meteor trail. Each station can then send and receive traffic alternately or simultaneously at data rates of up to many thousands of bits per second per frequency channel during the life of the trail. Many frequency channels can be operated simultaneously and high average rates can be achieved.

1.2 MBCS APPLICATIONS AND PERFORMANCE

The intermittent nature of the MBCS propagation path makes it particularly suitable for short messages which can be transferred via a single ionized meteor trail. Such a system was demonstrated in the Hawaiian area during the last half of 1983 when a MBCS was used for a Blue Force Location Management System. This system allowed for each ship's position to be communicated to all ships and stations of an operating unit (reference 2). The length of the "message" was about 30 characters.

For longer messages, "piecing" is typically employed. The portion of the message which is not transferred by the first meteor trail, because it dissipates too quickly, is transferred by succeeding meteor trails. The message is then pieced together. Table 1.1 is an example of typical waiting times (the time between initiation of a message and when it is received at the other terminal). This information is extracted from reference 3 which describes a procedure for computing MBCS performance for various applications.

MBCS has been used aboard inflight aircraft for air-to-ground and ground-to-air message links (reference 4), as a communications relay on a high altitude (70,000 feet) free floating balloon (reference 1), and as part of a battlefield-sensor system for the U.S. Army (reference 5), to name just a few DoD applications that have been tested and demonstrated.

Table 1.1. Yearly average of message waiting time (minutes) for half duplex operation at 50 MHz with message piecing, 4 kbps data rate, transmitters provide 1 kW power, antenna gains are 15 dBi at master station and 7 dBi at remote station, range of link is 800 st. miles and galactic noise is assumed.

Message Waiting Time (minutes)

Probability of Message Receipt	Message Length (Characters)				
	30	70	130	350	500
0.9	0.43	0.56	0.64	0.97	1.18
0.95	0.56	0.72	0.80	1.20	1.42
0.99	0.89	1.06	1.18	1.63	1.93

MBCS has also been used to provide a communication link employing message piecing that allowed traffic flow equal to 1-to-30 teletype circuits of 50 baud each operating continuously (reference 6). It is currently being tested and evaluated by the USAF and DCA for use as a survivable system during transattack within NORAD.

Much greater message capacity than indicated above is possible because the propagation medium will support instantaneous data rates of more than 1/2 mbps (reference 7). Actual data rates of up to 38.4 kbps have been demonstrated. Most systems have been operated at 2 to 8 kbps in the past.

1.3 COVERTNESS AND VULNERABILITY PROPERTIES OF MBCS

1.3.1 The Master Station

When a message is to be sent in either direction on a MBCS link, continuous probing of the propagation medium must occur so that suitable meteor trails can be detected and used. The master station performs this probing function and is therefore the most susceptible to detection by an interceptor or interference by a jammer. However, it is more difficult for a distant interceptor to get a bearing on the MBCS master station than it is to get a bearing on a system where propagation only occurs along great circle paths. This is because meteor burst communications occur on paths other than great circle paths (except when within groundwave range) and the direction of arrival of the signal is always changing from meteor-to-meteor.

If additional security for the master station is desirable and it is located near a populated area with a TV broadcast station, the broadcast station could function as the probing signal, thus allowing the "master station" to remain covert.

1.3.2 The Remote Station

The remote station is much less likely to be detected than the master station. The remote station's vulnerability depends on the proximity of an interceptor/jammer, as explained in the following discussion.

1.3.2.1 A Distant Interceptor/Jammer. A distant remote site normally transmits only when the site receives the master station signal because a meteor trail supporting the MBCS is present only then. The distant jammer or interceptor of the remote station, illustrated in figure 1.2, can be effective only if a second meteor trail supporting the remote to jammer/interceptor link occurs simultaneously. Enhanced security and antijam protection are provided by the very low probability that such a meteor trail would occur simultaneously with a meteor trail supporting communication between the master and a remote station, i.e., the target of the jamming. The interception of transmissions at a distant site would similarly require simultaneous occurrence of a second meteor trail capable of linking the transmitting station and the intercepting site, also an unlikely event. The limited amount of data reported that illustrates this phenomenon indicates a probability of a few percent (references 8, 9, and 10).

1.3.2.2 Interceptor/Jammer Near MBCS Stations. If the jammer or interceptor is near the remote site so that it is within ground wave range it can of course be effective. Reflection of signals from aircraft may also be important out to a couple hundred miles.

The jammer or interceptor can also affect the remote site if it is within the indicated elongated area (called the "footprint") surrounding the master station in figure 1.2. At the center of the footprint, where the master station is located, an interceptor/jammer would establish connectivity with the remote site every time the master station does. The probability of simultaneous occurrence of connectivity on the master station-remote station link and interceptor/jammer-remote station link decreases as the distance between the interceptor/jammer and the master station increases. The dashed line in figure 1.2 is a locus of points outside of which the probability is less than 0.25. The contours of equal probability have been described as ellipses, and some limited measurements of the size of the 0.25 probability correlation ellipse indicate the minor and major axis are about 50 and 200 km, respectively (references 11 and 12).

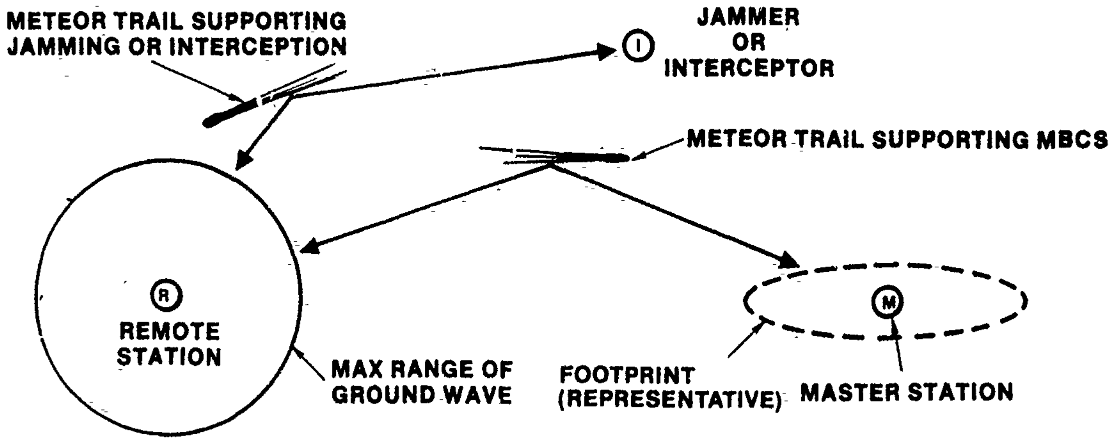


Figure 1.2. Plan view of an MBCS link illustrating interception and jamming.

1.3.2.3 Interception/Jamming for Nonmeteor Propagation. When sporadic E (E_S) ionospheric layers or tropospheric duct propagation conditions are present, the enhanced security and antijam feature of MBCS propagation is nullified because continuous connectivity is then possible over an extended area. Figures 1.3 and 1.4 illustrate the probability of occurrence of E_S around the world during May-to-August for day and night, respectively (reference 13).

Figure 1.5 illustrates the probability of surface-based tropospheric ducts occurring in the Pacific and Indian Oceans (reference 14). This phenomenon essentially extends the ground wave range to which the signal effectively propagates.

1.3.2.4 Methods of Improving Covertness of Remote Stations. If E_S or tropopsheric duct propagation is present, MBCS vulnerability could be partially mitigated by proper operating procedures. These propagation conditions in the master/remote link can be detected by the remote station. Because of the high probability of these same propagation conditions occurring simultaneously on an interceptor/remote site link, the remote station could refrain from responding to a received master station probe until this relatively infrequent propagation condition subsides.

Another possible method for improving the covertness of the remote station transmissions is to monitor and activate an automatic transmitter power reduction technique for minimizing detectability of the remote station transmissions. If a received master station probe is more than 20 dB above the noise level, the remote station could respond with 20 dB less power, thereby improving its covertness. This is feasible because the MBCS propagation path loss is expected to be reciprocal.

1.4 SURVIVABILITY ASPECTS OF MBCS FOR STRATEGIC COMMUNICATIONS

Of significant concern for communications systems used for strategic applications is their survivability in the nuclear war environment. The detonation of nuclear bombs at high altitudes, of the order of tens-to-hundreds of kilometers, produce a significant increase of ionization in the ionosphere. This increase in the D region of the ionosphere is responsible for significant absorption and blackouts in long-range ionospheric HF propagation links. This HF absorption has persisted for days. However, the absorption decreases as the frequency increases. Thus for the 40- to 50-MHz frequency range at which most MBCS have operated in the past, there can be much less absorption and a much more rapid recovery of communications links (references 15 and 16). This makes MBCS a good candidate for satisfying some requirements for communications during the trans- and post-attack periods of a nuclear exchange.

JUNE SOLSTICE, DAYTIME
MAP OF TEMPERATE ZONE Es OCCURRENCE
May, June, July and August; 0600-1800 Local Time
fEs > 5 Mc, 1948-1954

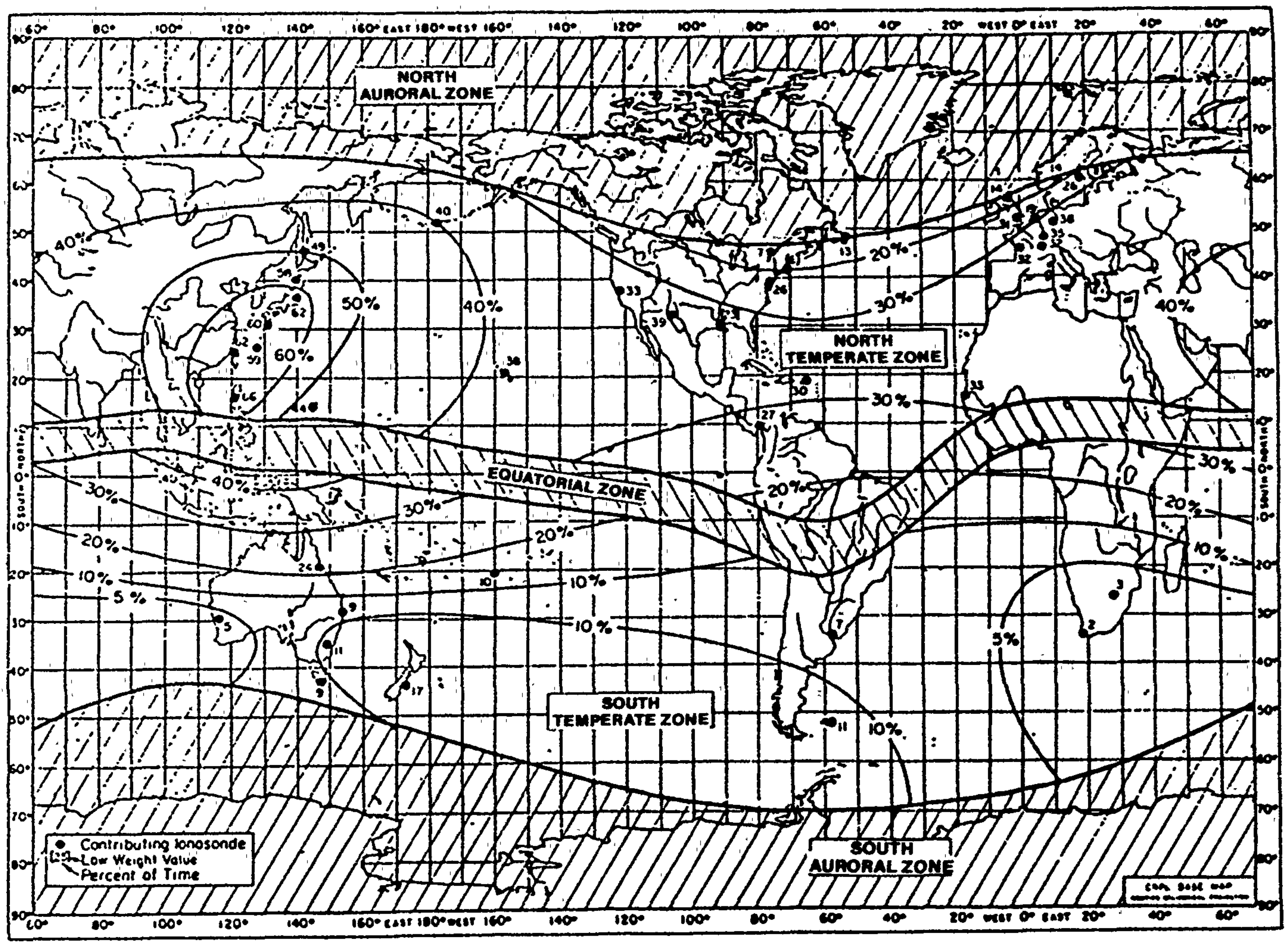


Figure 1.3. Global daytime occurrence of sporadic E, in % of time, from May-to-August.

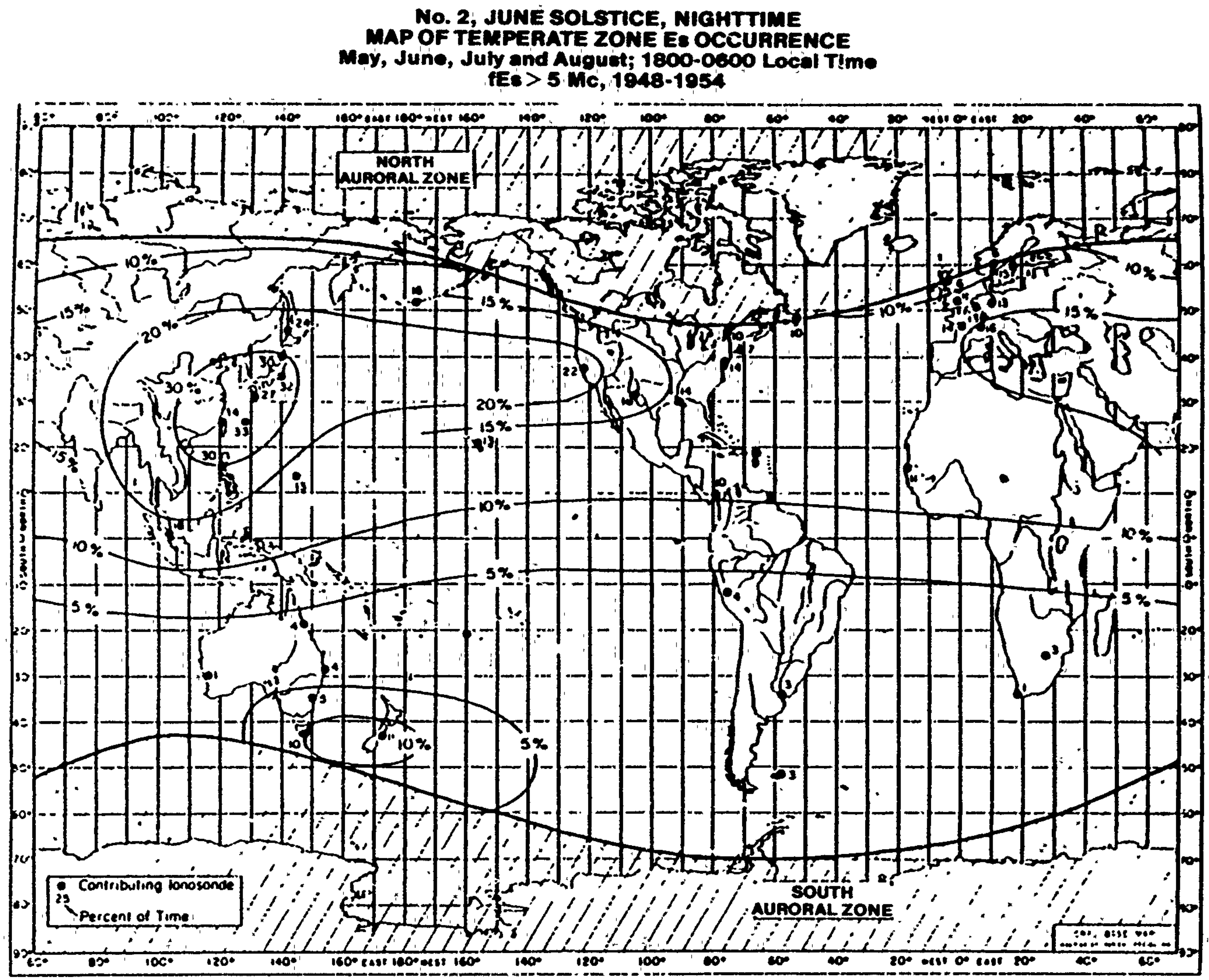
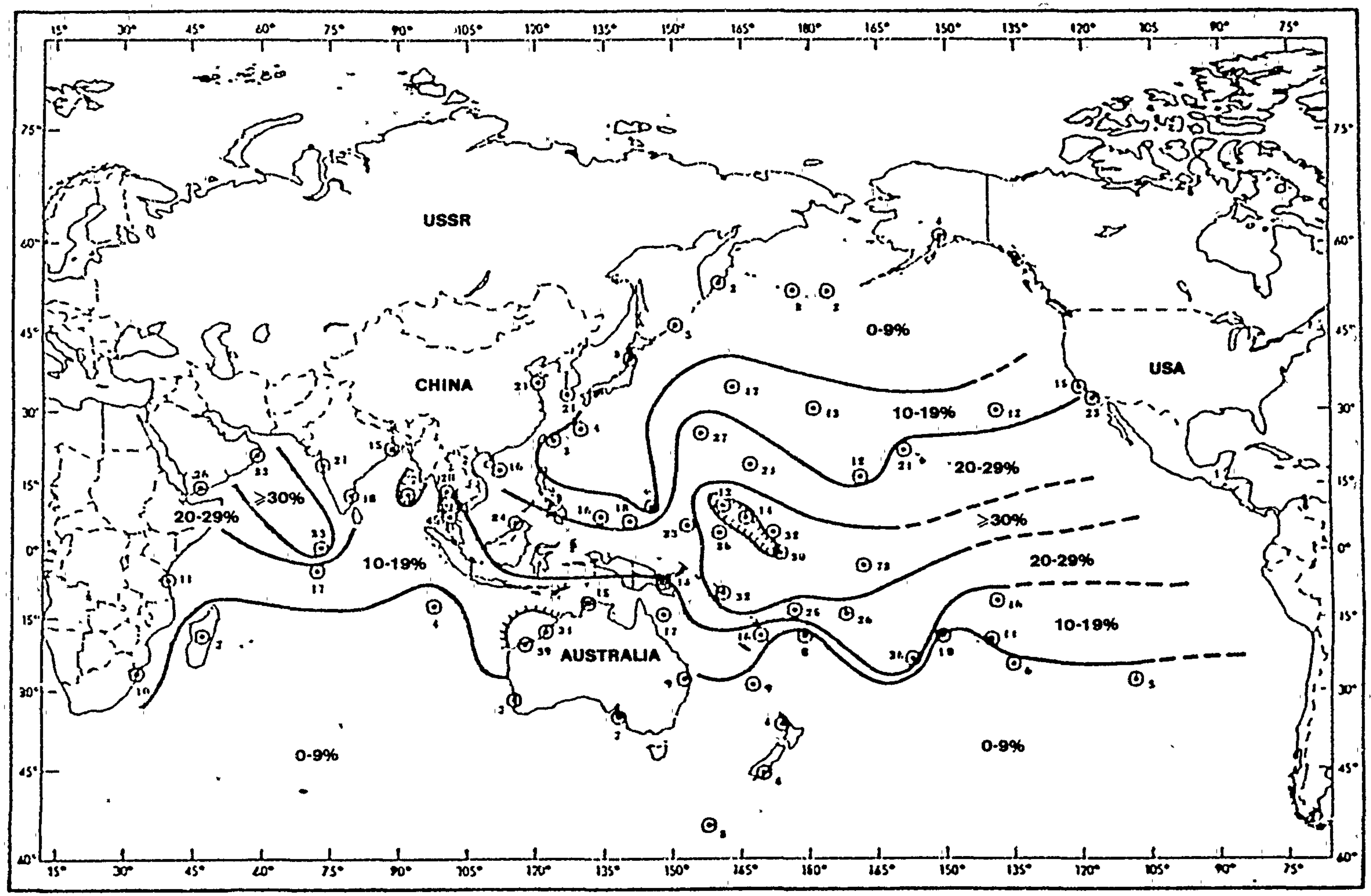


Figure 1.4. Global nighttime occurrence of sporadic E, in % of time, from May-to-August.



NOTE: Circled dots are weather stations; numbers are the average annual percent occurrence for that station.

Figure 1.5. Frequency of occurrences of surface based tropospheric ducts for the Pacific and Indian Oceans.

2.0 APPLICATIONS FOR BUOY RELAY MBCS

The unique covertness and survivability aspects of MBCS, which were discussed in preceding sections, make it a good candidate to consider for satisfying some communications requirements. Several of these requirements will be discussed here in order to identify some of the required MBCS features and characteristics, including primary power required of a buoy relay for the various applications. The primary power requirements determined below assume the same MBCS equipment installed on the buoy as was used on the balloon during its relay tests (reference 1), i.e., 620 watts when transmitting and 0.6 watt when not transmitting. The nominal RF transmitter power output was 300 watts.

2.1 RELAY BETWEEN SHORE AND LAND BASED SITES

Shore and land based communications facilities generally can have sufficient primary power available so that they could supply the 1 or 2 kW normally used by a shore-based master station. If maximum covertness of the shore site is not a critical requirement, the buoy relay could then function as the typical remote station, transmitting only when it receives a signal from a probing master station. A message, consisting of a string of bits that may or may not be encrypted, would be received from one master station and stored aboard the buoy system until it receives a probe from a second master station which needs the message, at which time the buoy transmits it. In this scenario, the buoy transmits very little, maximizing its covertness (to avoid pilfering or destruction by attack) and conserving its onboard primary power supply. The transmitter operating time typically required for the transfer a 130-character message at a 10-kbps data rate would be the sum of a 20-msec probe transmission to the first master station and a 100-msec transmission of the 130-character message to the second master station. If 20 such messages were relayed in an hour, the average power required by the buoy MBCS would be 0.7 watt for the receiver and processor and 0.2 watt for the 40 transmissions for a total of 0.9 watt within the hour.

When it is necessary to transfer the greatest volume of traffic through this relay, so that it is desirable to use every available meteor trail, the percent of time that the relay transmitter operates would be significantly greater. During August when the seasonal variation of meteor rate is the highest and at local sunrise when the diurnal variation of meteor rates is the greatest, the propagation path is useful for up to 10% of the time. The relay transmitter would then be operating perhaps up to 12% of the time (the extra 2% being due to link management overhead), consuming about 75 watts of power. The average power consumption through a typical August day would be about half as much.

2.2 RELAY BETWEEN SHORE SITES AND COVERT UNITS

2.2.1 Covert Unit Transmits a Message

Communications between covert units, such as submarines or surface ships, and a shore site through a buoy relay requires that the buoy operate, at least partially, as a master station. This is because of the need for the ship or sub to refrain from probing for meteor reflections. Such a buoy relay may operate in the half duplex mode. The balloon relay system described in reference 1 alternately transmits a probing signal for about 20 msec and then listens for a response for about 40 msec, repeating this continuously for a specified period of time or until a satisfactory response is received. This 1/3 duty cycle requires about 207 watts of power to operate the 300-watt transmitter. The shore system could also maintain its covertness and function as a "remote station" by responding only when it received the buoy probe signal from this continuously probing relay.

An alternate method of operation may be for the buoy to not normally transmit. When it is desirable to receive traffic from a covert platform, according to a prearranged random schedule, the shore site would probe the buoy and "turn it on" so that it could "probe and wait" for an expected message from the covert platform. Upon receiving the message it would then relay it on to the shore site and return to an idle state when this is accomplished.

2.2.2 Covert Unit Does Not Transmit

For an application in which it is only necessary for the covert unit to receive a shore site originated message, as in the case of an "Emergency Action Message" (EAM), the buoy relay would simply broadcast (repeat continuously) the message it received from the shore site for a time sufficient to assure a high probability that the entire message, after piecing, was correctly received. This relay procedure, described in reference 1, requires from 10 to 15 minutes, a period during which 620 watts of power were required for the 300-watt RF power radiated.

2.3 NETWORK OF BUOY RELAYS

If the operational requirement dictates an array of buoy relay systems in an ocean area, each would be monitoring only the frequencies the nearby sites or relays are programmed to operate on. When a shore or ship site initiates a message which is then received by buoy relays within the area, the buoys then revert to the probe and listen mode in order to send the message to other buoys which are monitoring the circuits. When this message is delivered to one or two other relays, it may then revert to its previous "monitoring" mode of operation.

In such a scenario as this, the power required for the buoy system is again a function of the message volume. Each buoy relay in a network operating at maximum throughput may, to a first approximation, be attempting to send the message half the time and receive another message the remaining time. Since the transmitter duty cycle during the sending mode is about 1/3 (20 msec on and 40 msec off), an overall transmitter duty cycle of 1/6 would be obtained. This requires an average power of about 103 watts for a 300-watt transmitter.

A summary of the applications discussed in this section and the respective buoy power requirements are tabulated in table ES.1.

3.0 ANTENNAS

3.1 GENERAL

Several considerations and design/performance trade-offs determine the selection of the type of antenna for the buoy-relay application where the 45- to 50-MHz band is assumed. These include polarization preference (vertical or horizontal), antenna radiation patterns, gain, propagation, sea-state effects, mechanical design considerations (weight, windload, support needs), antenna impedance stability, and operational requirements. The same polarization is used on each end of a MBCS link because theory and test results indicate that normally there is very little cross-polarization conversion occurring on the propagation path.

The selected antenna height above the sea is a compromise among

1. the details of the vertical plane radiation pattern, especially at the lower elevation angles which are of interest for maximum communication ranges;

2. having sufficient height so the antenna "looks over" a significant percentage of the larger waves;

3. minimizing wind load;

4. having sufficient height to avoid most breaking waves; and

5. the mechanical requirements of support, guying, and surviving sea state 9 if possible.

General references to antennas include numbers 17 through 21.

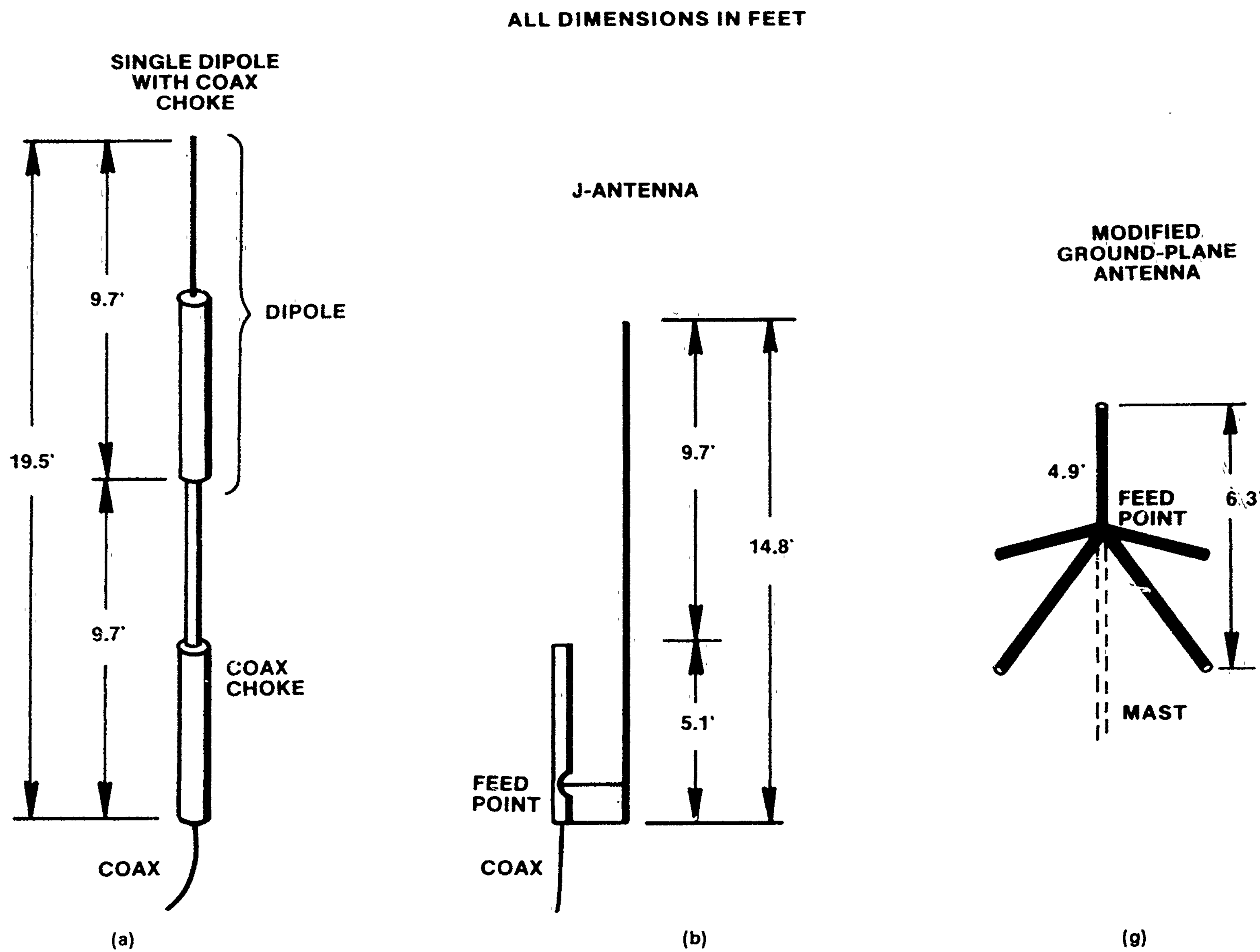
3.2 ANTENNA CHARACTERISTICS

3.2.1 Types

The generic antenna types possibly suited for use on a buoy relay include (some sketches are shown in figure 3.1)

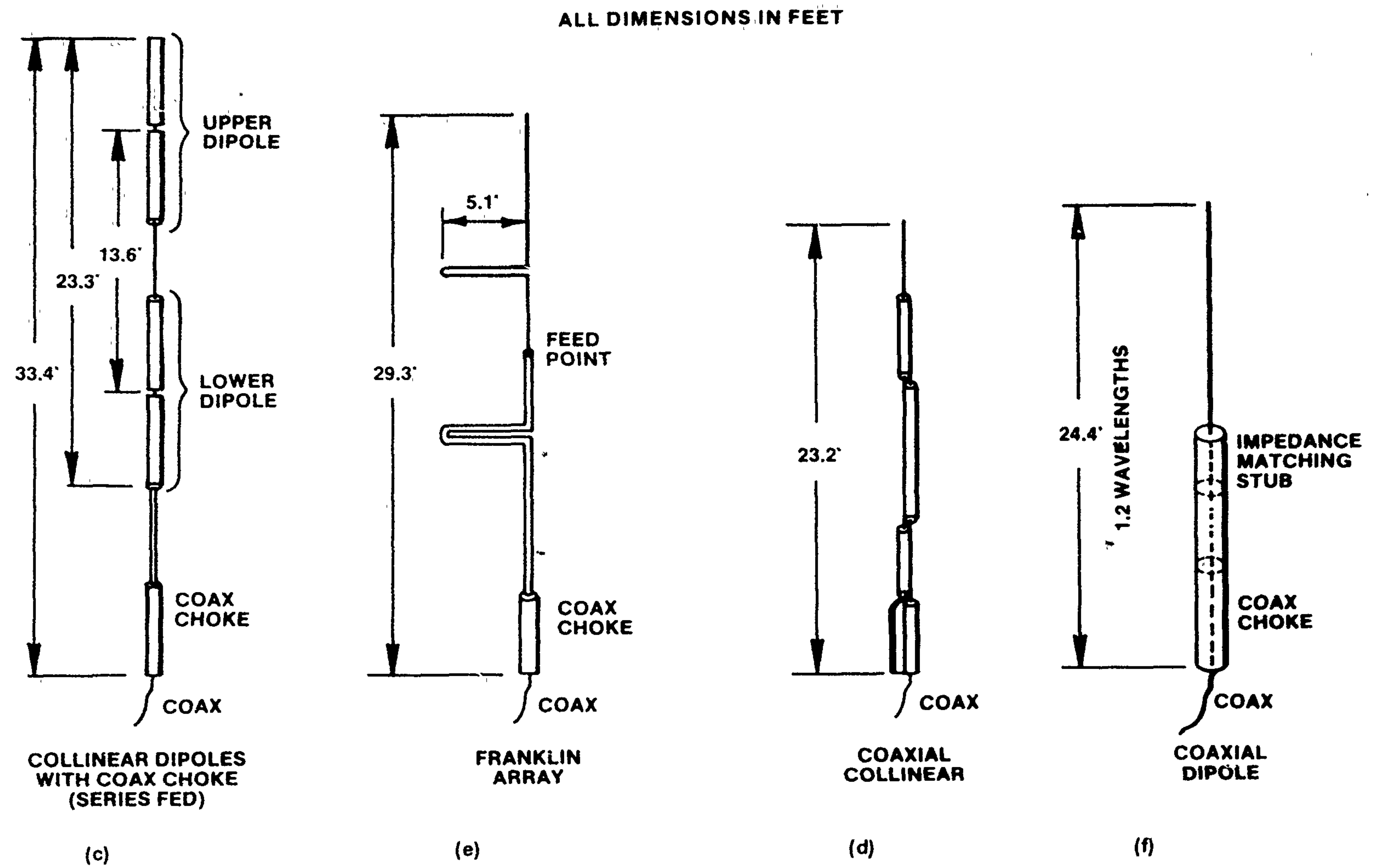
- vertical halfwave element (e.g., dipole, J-antenna)
- vertical collinear dipole array
- crossed horizontal dipoles
- stacked crossed horizontal dipoles
- multi-element beam (Yagi-Uda or log-periodic antenna)
- loop(s) (vertical or horizontal)
- sleeve monopole
- modified ground-plane antenna

3.2.1.1 Vertical Halfwave Antenna. Vertical halfwave elements may be a simple halfwave (9.8 feet at 48 MHz) dipole (figure 3.1(a)) or a J-antenna (figure 3.1(b)) whose overall length is about 0.74 wavelength (14.8 feet). Both have similar performance, i.e., are omnidirectional with about 5-dBi gain. The J-antenna has the advantage of being reasonably well isolated from the coax and supporting structure beneath it (i.e., not having induced RF currents which would cause pattern distortion and impedance changes). The vertical dipole requires special design care to ensure isolation from what is beneath (or above) it.



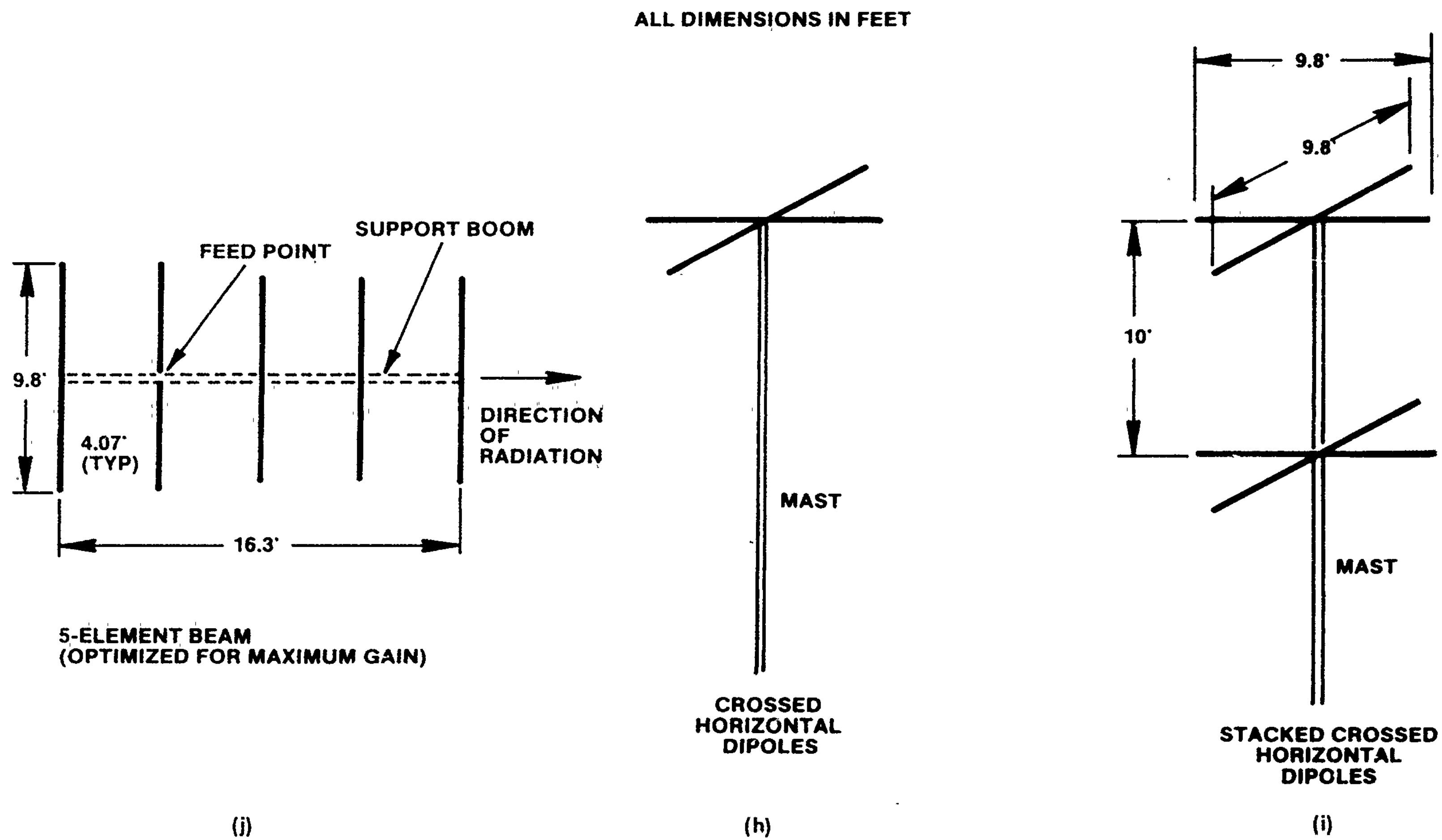
Sketches (a, b, and g) of MBCS buoy antenna types being considered.

Figure 3.1. Sketches of MBCS buoy antenna types being considered.



Sketches (c, e, d and f) of MBCS buoy antenna types being considered for the 45-to 50-MHz band.

Figure 3.1. Sketches of MBCS buoy antenna types being considered (cont).



Sketches (j, h and i) of MBCS buoy antenna types being considered for the 45- to 50-MHz band.

Figure 3.1. Sketches of MBCS buoy antenna types being considered (cont).

3.2.1.2 Vertical Collinear Dipole Array. An array of two vertical collinear dipoles (figure 3.1(c) or 3.1(d)) is being considered because it offers the possibility of increased gain (up to 3 dB) at lower elevation angles. It will require an assembly about 35 feet in length at 48 MHz. The design of collinear dipoles must also address the above mentioned problem of stray RF currents on the outside of the coax and supporting structure in order to maintain control of the antenna's pattern and impedance. There are several approaches for collinear dipoles (or an antenna of equivalent performance). However, all designs will require RF chokes either as coaxial line sections or as lumped inductances, and/or special phasing lines all in order to maintain proper distribution of RF currents. Collinear arrays may be fed with concentric coax or be series fed with a single coax. To achieve the needed quality of performance requires dimensional precisions (tolerances) not normally associated with antennas at these frequencies.

Other antenna approaches may be used to achieve similar higher gain and narrow vertical beam width as the collinear dipole; for example, a modified Franklin (figure 3.1(e))), or a single coaxial dipole (figure 3.1(f)) of about 1.2 wavelengths (24.4 feet). The advantage of these vertical dipoles and arrays is mechanical simplicity, but the impedance bandwidths may be inadequate.

3.2.1.3 Crossed Horizontal Dipoles. A crossed horizontal dipole array is an easy antenna to fabricate. The major problem is the great height (about 40 feet) required to achieve reasonable gains at the lower elevation angles necessary for effective MBCS performance. Two sets (pairs) of horizontal crossed dipoles, one pair 10 feet below the other, is a possible arrangement that can improve gain at the expense of increased wind load and weight.

3.2.1.4 Multi-element Beam. Multi-element beams, as the Yagi-Uda antenna, provide a directed unidirectional beam with increased gain. For higher gains and narrower beamwidths, longer lengths and increasing numbers of elements are required.

An "optimized" five-element beam (figure 3.1(j)) will have a gain of 11 dBi for its 16-foot length (ref.). Commercially available five-element beams of 9-foot lengths have gains of about 8 dBi. This antenna type may be used for azimuthal directivity (see 3.7.1) or for a vertically directed beam (see 3.7.2).

3.2.1.5 Horizontal Loops. Horizontal loops have been used in the past for meteor burst communications tests when mounted beneath a high-altitude balloon (reference 1). An array of four provided horizontal polarization, with gains about 5 dB above a dipole. Because of the higher selectivity, required tuning, relatively large surface area, and tall heights, this approach is not being seriously considered for the buoy. Dependency upon tuning may seriously affect antenna reliability, especially if subjected to long-term storage and to deployment in rough seas.

3.2.1.6 Sleeve Monopole. A whip antenna mounted above a metallic support mast is essentially a sleeve antenna. The whip need not necessarily be 1/4-wavelength (5 feet) long. The complete antenna consists of the whip, the mast, and the portion of the buoy between the base of the mat and the seawater. This is a mechanically simple antenna. However, the electrical characteristics are not simple, as the hardware and geometry beneath the whip are at least as important to the performance of the antenna, as the whip itself is. All calculations and measurements of antenna characteristics and performance must include the whip, the mast, anything attached to the mast, and the exposed part of the buoy. Any changes to metallic items below the whip will likely necessitate re-evaluating the performance of the sleeve monopole. Any change of water level relative to the sleeve monopole will affect the antenna's performance.

3.2.1.7 Modified Ground-plane Antenna. A ground-plane antenna will somewhat isolate the whip (monopole) from the environment (e.g., supporting structure) below. A typical ground-plane antenna is a quarter-wavelength vertical monopole fed against a ground plane of four, equally spaced, quarter-wavelength radials lying in a horizontal plane perpendicular to the monopole. The maximum radiation is directed skyward at some angle above the horizon which may not be desirable.

A modified ground-plane antenna (figure 3.1(g)) can improve radiation toward the horizon by having the four ground-plane radials mounted at a downward angle (45° or 50°) below the horizontal (reference 21).

3.2.2 Polarization

Propagation, sea-state effects, and radiation patterns differ for vertical and horizontal polarizations. The electrical properties of seawater, relative permittivity of 80, and conductivity of 4 or 5 mhos/meter affect the reflection behavior of vertical and horizontal polarization differently. The principal resulting difference is the higher gains available at the lower elevation angles with vertical polarization.

It is important for MBCS to be implemented with antennas of the same polarization on each end of a link. There is very little cross polarization, i.e., conversion of incident radio wave energy from one polarization to the other on reradiation. Constraints of the antenna type that may be installed at the other end of a link can dictate the antenna polarization which must be used on a buoy relay.

3.2.3 Radiation Patterns

Three sets of calculated radiation pattern information are presented for three different antenna arrangements:

Figure 3.2(a) and 3.2(b) are for a single vertical dipole;
Figure 3.3(a) and 3.3(b) are for two vertical collinear dipoles;
Figure 3.4(a) and 3.4(b) are for two horizontal crossed dipoles.

All the radiation patterns are in the vertical plane with the antennas located over a flat seawater surface (no waves) and assume 100% antenna efficiency (no losses within the antenna). A frequency of either 50 or 48.38 MHz was assumed for these calculations made using the Numerical Electromagnetic Code (NEC) computer program.

The vertical antennas have horizontal plane patterns that are azimuthally omnidirectional. The crossed horizontal dipoles have a horizontal plane pattern that is nearly omnidirectional, the range of gain being represented in the patterns as a pair of lines which closely parallel each other. As a point of reference, a half-wavelength dipole in free space has a gain of 2.1 dBi (dB relative to an isotropic radiator).

3.2.3.1 Vertical Dipole. The single vertical dipole (figure 3.2(a)) has the lowest gains for heights greater than about 13 feet. At lower heights, its gain exceeds 5 dBi. The half-power beam widths and the elevation angle of the null above the lowest pattern lobe is adequate to allow effective communications at ranges beyond about 400 km. Analysis for a single vertical dipole located 10 feet above seawater and tilting 15 degrees shows a gain decrease of 0.5 dB for the main (lowest) lobe (6 degrees elevation angle) and also a 0.5 dB decrease at 2 degree elevation angle. These seeming low variations in gain are held low because of the intrinsically wide radiation pattern of a dipole. The first null above horizon fills in (i.e., is not as deep) as the dipole tilts, the least change occurring perpendicular to the plane of the tilt.

3.2.3.2 Collinear Vertical Dipole Array. The collinear vertical dipole array (figure 3.3(a)), spaced 0.9-wavelengths apart (18.2 feet c-c), have relative narrow beam widths that will require a buoy to have less roll. For a 15-degree tilt of the antenna, the gain variation at the peak of the lowest lobe (at 4-degree elevation angle) is 3 dB.

3.2.3.3 Crossed Horizontal Dipoles. A pair of horizontal crossed dipoles (figure 3.4(a)) has a much broader pattern lobe, with less gain than a single vertical dipole, typically, from 0.5 to 1.5 dB less at pattern maximum. The maximum gain occurs at a higher elevation angle which is not desireable for longer ranges. And the gain differential at the lower elevation angles, say 5 degrees or less, is even greater. Gain increases at the lower elevation angles as the horizontal antenna is raised in height. Thus, one pair of horizontal crossed dipoles may be a disadvantage. A second pair of crossed dipoles located 10 feet below the other pair may be used to achieve added gain toward the horizon and to minimize energy directed overhead.

3.2.3.4 Lower Elevation Angles. It is also instructive to look at the gains at 1.5 degrees elevation for each of the three antenna types. (The 1.5 degrees is an arbitrary choice, but reasonable when maximum range is desired of this system.) The table below summarizes this data:

Lower Elevation Angles

Type of Antenna	Height (feet)	Approx. Gain (dBi) at 1.5 degrees elevation
Single vertical dipole	6.6	2.7
	16.4	1.4
Collinear vertical dipole array	6.6	4.2
	19.7	2.4
Crossed horizontal dipoles	10.0	−13.0
	40.0	1.5*

*From pattern data not presented in text.

Wide band antennas directed toward the horizon will have gains comparable to the above, but changed approximately in proportion to any free-space gain difference.

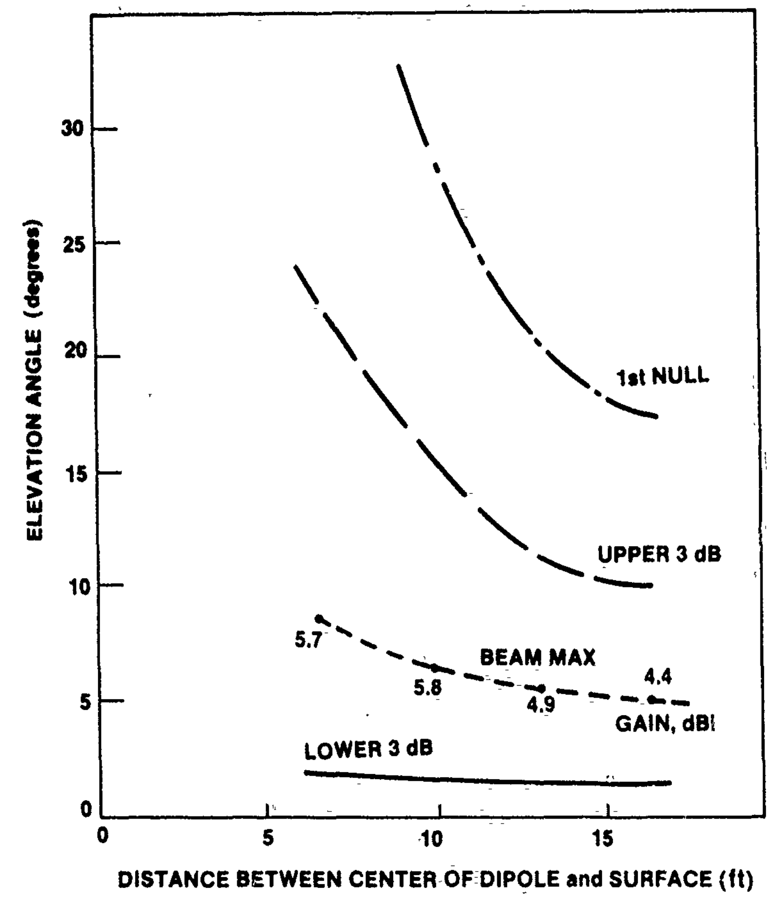


Figure 3.2(a). Vertical plane radiation pattern summary of a vertical dipole above seawater for 50 MHz.

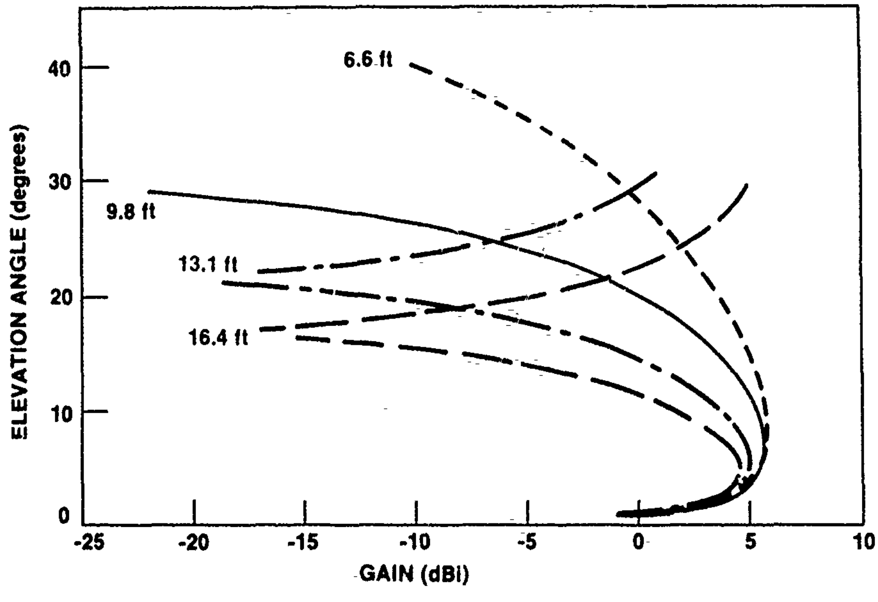


Figure 3.2(b). Vertical plane radiation pattern of a vertical dipole 6.6, 9.8, 13.1, and 16.4 feet (2, 3, 4, and 5 meters) above seawater at 50 MHz.

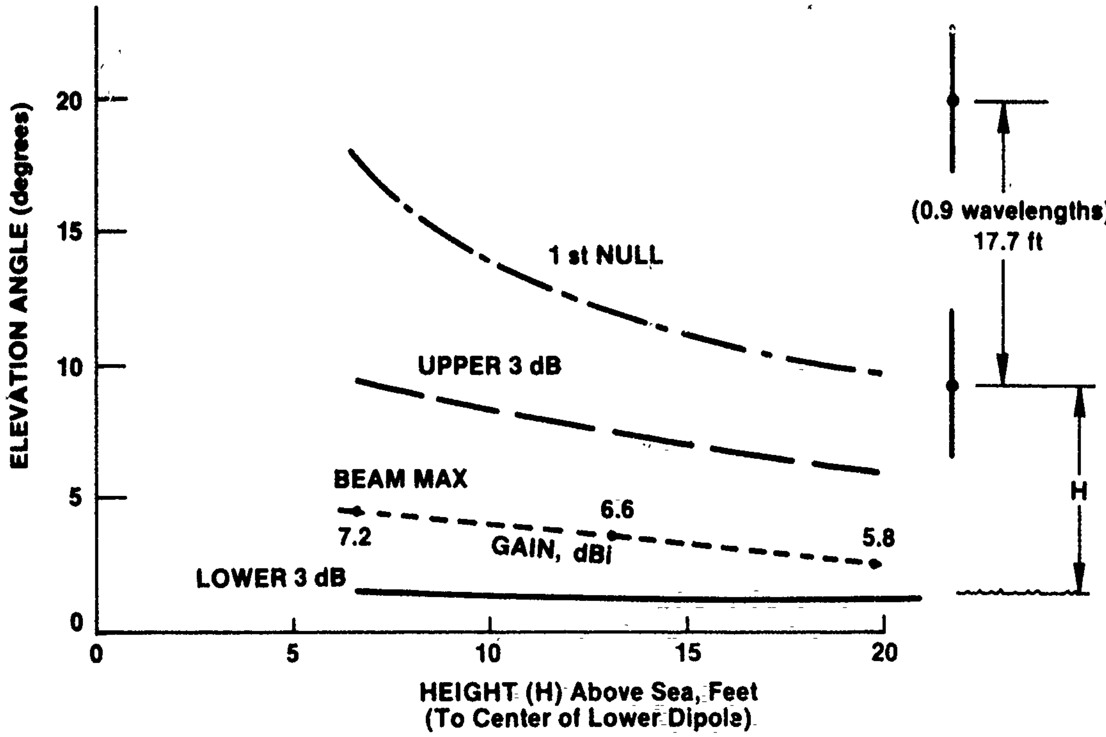


Figure 3.3(a). Vertical plane radiation pattern summary for two vertical collinear dipoles, with spacing of 17.7 feet (5.4 meters; 0.9λ) between their centers, at 50 MHz. The height above sea refers to the height of the center of the lower dipole above the sea.

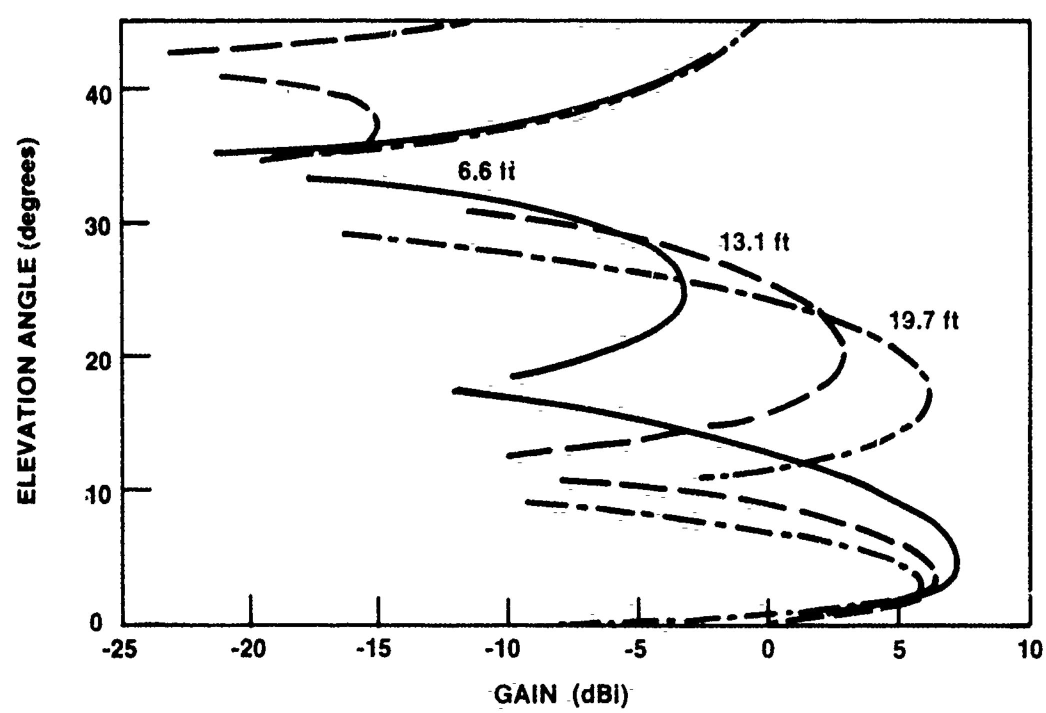


Figure 3.3(b). Vertical plane radiation pattern for two vertical collinear dipoles, with spacing of 17.7 feet (5.4 meters; 0.9λ) between their centers, at 50 MHz. The height of the center of the lower dipole above the sea is 6.6, 13.1, and 19.7 feet (2, 4, and 6 meters).

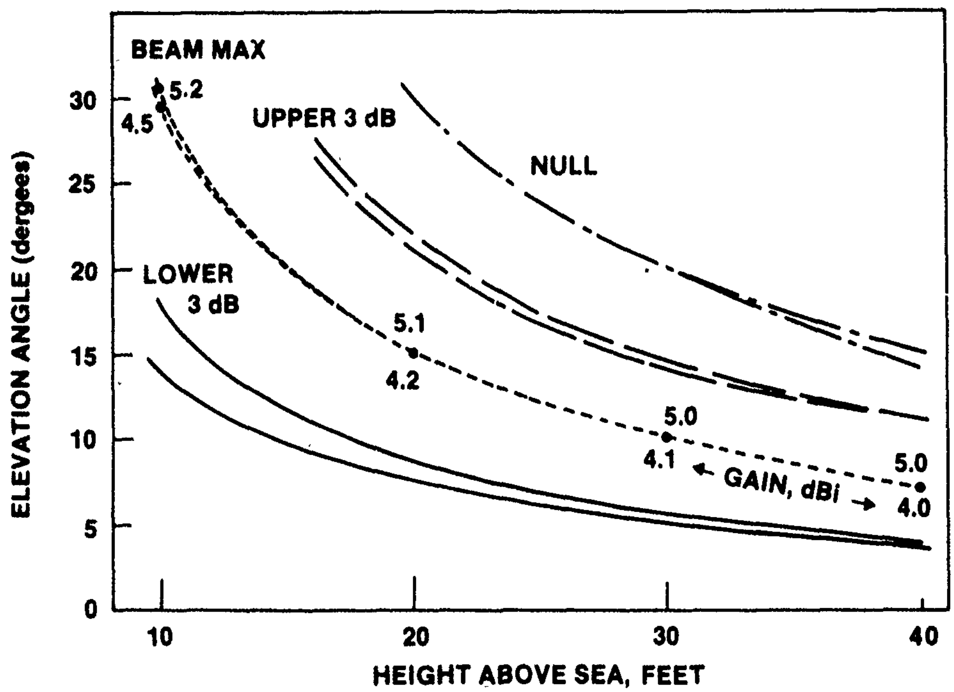


Figure 3.4(a). Vertical plane radiation pattern summary for crossed horizontal dipoles above seawater for 48.4 MHz.

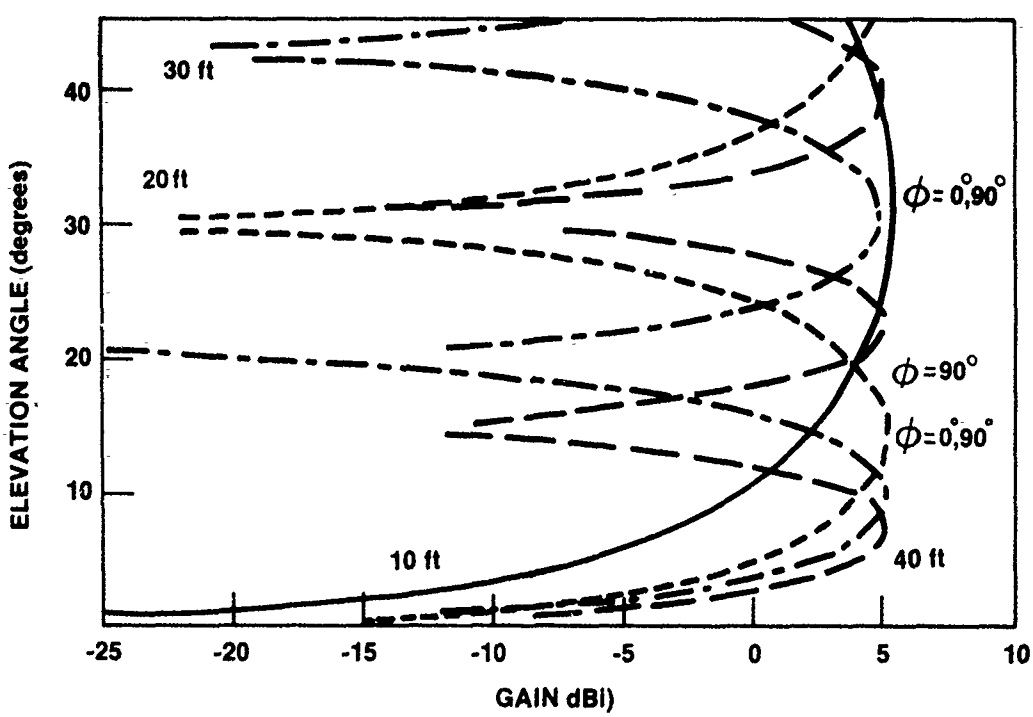


Figure 3.4(b). Vertical plane radiation pattern o:' crossed horizontal dipoles 10 feet (3.0 meters) above seawater at 48.4 MHz. ϕ is azimuthal angle.

3.2.4 Bandwidth Requirements

MCBS links typically operate with master and remote stations transmitting on different frequencies. On the buoy, a transmit/receive switch will alternately connect the transmitter or receiver to the single antenna system as needed. A "narrow band" antenna system should be tuned to the transmit frequency to maximize radiated power. The bandwidth of this antenna and the difference between the transmit and receive frequencies should be such so that no more than several dB of the received signal is lost due to the receive system mismatch. An antenna bandwidth of 10% is generally adequate.

3.2.5 Efficiency

Any half-wavelength dipole type antenna (except for a horizontal dipole very close to the water) will be very efficient with losses being generally less than 0.1 dB. Losses will occur mainly in the coaxial transmission line, and in any power divider if used. Twenty feet of RG-214/U coax has 0.3 dB loss. A power divider may have about 0.5 dB loss.

3.3 EFFECT OF SEA STATE

Sea state affects the antenna radiation pattern shape and gain since approximately half of the contribution to the pattern is from reflections from the sea surface. An irregular surface causes the reflected energy to become randomly scattered in both amplitude and phase. Since, as stated above, seawater affects horizontal and vertical polarizations differently, the effects of sea state upon radiation of different polarizations will differ.

Figures 3.5, 3.6, and 3.7 (from reference 22) show the added transmission losses expected for ground-wave propagation of vertical polarization at 50 MHz for various sea states. The loss decreases with increasing elevation above ground. The results in figure 3.7 indicate that an assumption of a rough sea would not alter significantly the antenna pattern calculations discussed in section 3.2.3.

Ground-wave, as defined by Barrick,[22] is the total field observed at a point in space, excluding any component reflected from the ionosphere or discontinuities in the upper atmosphere. The ground wave consists of a space wave and a surface wave. The space wave consists of the direct wave and that reflected from the earth. The surface wave is the field remaining of the ground wave after the space wave has been subtracted. Figure 3.7 indicates that a 10° elevation angle, where the space wave dominates, the rough sea model causes a 0.6-dB decrease in signal level over the smooth sea model.

Degradation of antenna radiation can occur if it is in a wave trough. Any wave higher than the antenna will block low-angle radiation in that direction. Some diffraction around the wave crest will occur.

A vertical polarized antenna will exhibit less impedance excursion due to varying distance above seawater than a horizontal antenna. This is because of the limited radiation off the end of the vertical dipole, while a horizontal dipole will receive back most of the energy incident upon the sea surface below it.

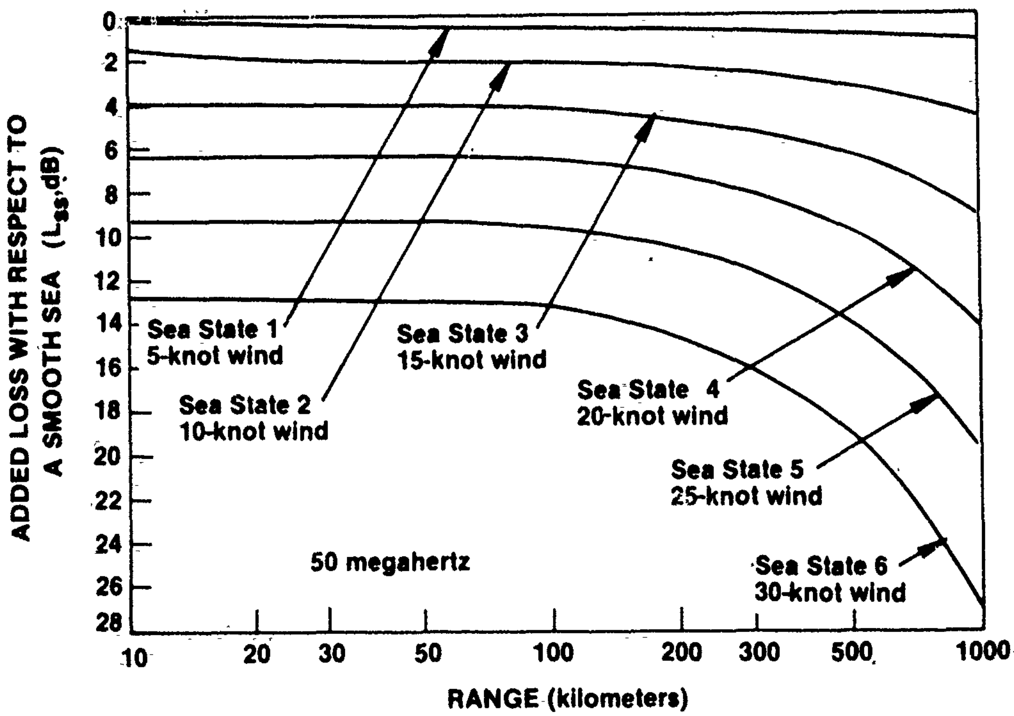


Figure 3.5. Added transmission loss due to sea state at 50 MHz. Antennas are located just above surface. Neumann-Pierson ocean-wave spectrum with propagation in upwind-downwind direction.

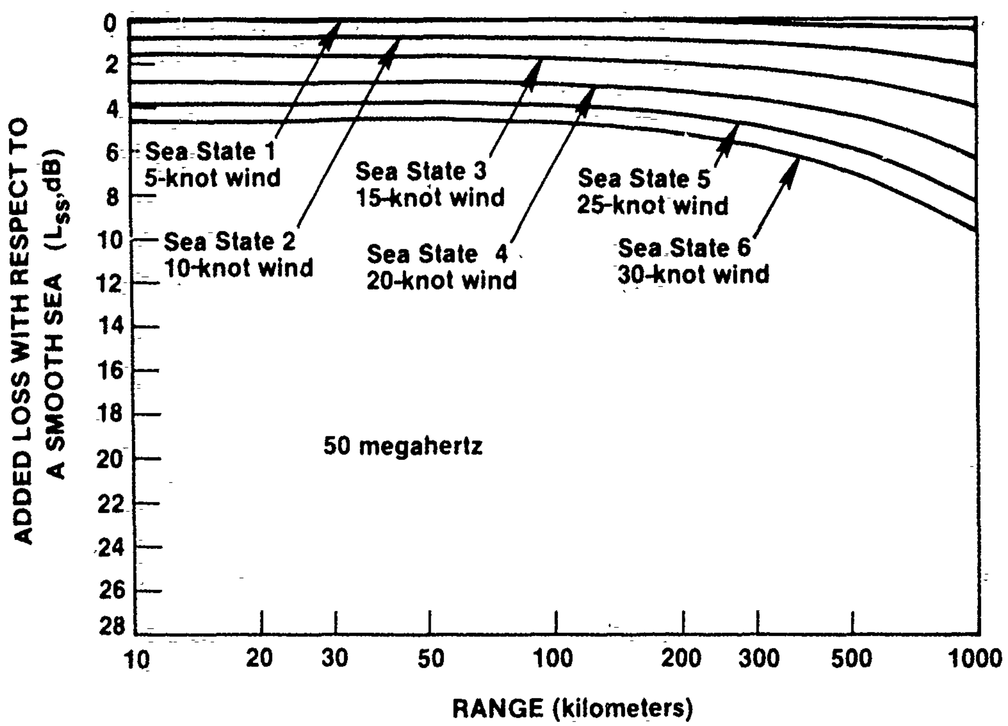


Figure 3.6. Added transmission loss due to sea state at 50 MHz. Antennas are located just above surface. Neumann-Pierson ocean-wave spectrum with propagation in crosswind direction.

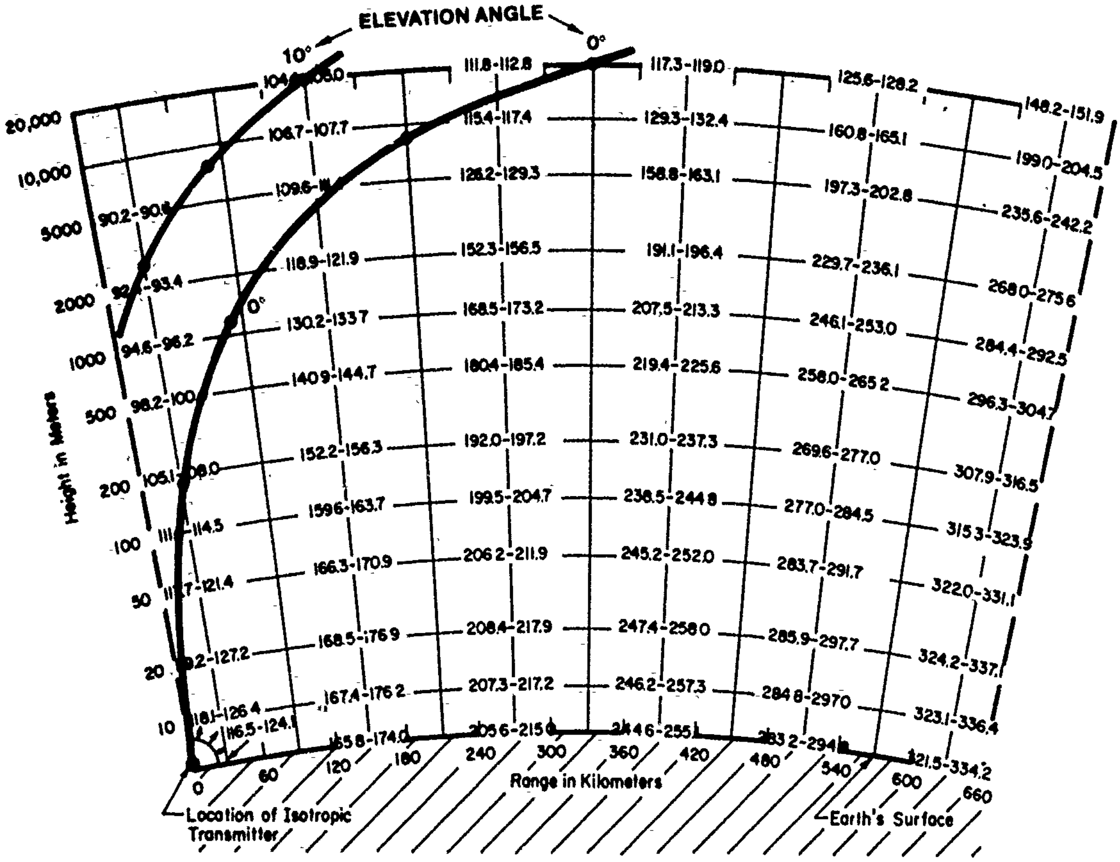


Figure 3.7. Basic transmission loss to points at various heights and ranges above the ocean at 50 MHz. First number is for perfectly smooth sea, second is for sea state 5 (25 knot wind) using Phillips ocean-wave spectrum.

Wetting of the feed point of any radiator with seawater will cause a decrease in radiated power due to losses across the driving voltage. Wetting of the radiator itself causes no problems as the radiator is already a good conductor. The best approach for the feed point area is that it be designed to shed water as rapidly as possible, and to not trap any standing water, and to use water-phobic materials from which contaminants will not readily adhere.

3.4 MECHANICAL/PHYSICAL CHARACTERISTICS

Size, weight, wind loading, guying needs, and center-of-gravity are some of the principal mechanical characteristics of interest. Any successful antenna design is the result of good mechanical as much as electrical design, since an antenna is a mechanical apparatus doing an electrical function. For a buoy-mounted antenna, the main items of concern from a mechanical viewpoint are the wind-induced stresses and the dynamic forces due to motion of the buoy, minimizing wind resistance, and minimizing weight without sacrificing ruggedness, and possibly the selection of alloys that will provide the reliability of electrical contact in a salt-laden environment. Of course, the supporting mast and guying must do the job with minimal windloading. The needed roll stability of a buoy is dictated by the allowable variation in antenna gain.

Special design(s) for a final model that is easily and reliably deployed by semi-skilled personnel will depend upon the application and the vehicle(s) used for transporting and launching. Foldable antenna techniques may be necessary so the buoy and antenna may be stowed, transported, and launched with the needed reliability and safety. A dielectric sheath (e.g., fiberglass radome) could be used over a dipole or collinear dipole antenna to protect it from weather, sea spray and damage, and to provide a degree of mechanical support. If used, such an enclosure will limit the options for "foldability."

3.5 RF POWER CONSIDERATION

RF power levels of 300 watts, delivered to the antennas by the equipment used in the balloon relay tests (reference 1), should pose no undue development risk. The fact that the antenna diameter cannot be small because of the needed bandwidth, will assist in handling high RF voltages. RF leakage path across the feed point should be made as large as practical because of the moist salt (conductive) film that will form on the insulator. Dielectric heating of insulators will be no problem when the system is operated at low duty rate of the transmitter; but may be a consideration if the transmitter operates at 50 percent duty cycle or more.

3.6 MONITORING ANTENNA RF PERFORMANCE

Directional couplers for monitoring forward and reflected RF power can be used to indicate the antenna's performance. The ratio of the two is used to determine SWR (Standing Wave Ratio). The forward power directional coupler also shows the transmitters output power. A low (good) SWR is not an absolute guarantee of good antenna performance and condition, but if the SWR is higher than normal then something is definitely amiss. Sea spray icing, which increases antenna system losses, is an example of an occurrence that is not necessarily indicated by an increase in SWR.

3.7 FUTURE CONSIDERATIONS

Some antenna types are discussed that may find use for special candidate potential applications.

3.7.1 Beam Antenna On Buoy

Additional antenna gain and/or enhanced covertness resulting from a directed radiation pattern can be achieved by using a multi-element beam antenna (figure 3.1(d)) on a buoy. The complexity and cost would be considerably greater than for a fixed omnidirectional antenna.

Additional equipment is required to allow use of such an antenna:

1. to let the antenna "know" the proper bearing to steer;
2. a drive system to turn the antenna to the desired direction;
3. the additional energy capacity to power the drive system.

3.7.2 Vertically Directed Antenna

An application requiring a vertically directed antenna for the buoy relay might involve use within a task force whose separation across the sea surface would not be large. Meteor trails above 45° elevation angles would be of use. The antenna for this use could also be a multi-element beam or Yagi-Uda antenna. Almost all the radiated energy would be directed upward from a vertically directed antenna. These antennas can be designed for higher gains than an omnidirectional antenna and for very little signal going toward the horizon, thus increasing the covertness of communications. It is likely that this antenna could be placed closer to the water since there is no concern about how the sea affects the pattern and about obstruction caused by the higher sea waves at the extreme lower angles.

3.7.3 Low Radar Cross Section (RCS)

A degree of physical covertness may be achieved if the buoy and its superstructure above were difficult to detect with radar. Obviously, the more metal in the antenna, support and guying, the easier for detection by radar. There may be some techniques applicable to minimizing the Radar Cross Section (RCS). It is believed that for a low RCS, an entirely different antenna approach is require such as an upward directed slot antenna. The end result may be an antenna with less gain.

3.7.4 Frequency Agility

Frequency agility usually implies a relatively wide range of frequencies. Wide bandwidths for antennas require larger dimensions. Antennas of few elements have elements of larger diameters, or antennas may have more elements such as log-periodic antennas.

Alternatives to larger dimensions include dynamic antenna tuning and resistive loading. Dynamic antenna tuning is achieved by electronically tuning (matching) for each frequency used, at the expense of increased complexity and decreased reliability. Resistive loading "smooths out" the Standing-Wave Ratio (SWR) at the expense of decreased antenna efficiency.

4.0 MBCS PERFORMANCE VS ANTENNA CHARACTERISTICS

Considerable theoretical and experimental work has been conducted in meteor trail scattering since the late 1940's when MBCS was first tested. As a result, detailed physical and mathematical relationships that describe various aspects of the phenomenon have been developed and are available for making performance predictions (reference 23).

Haakinson (reference 24) has used the available information to develop a meteor burst communications model that predicts the performance of meteor burst communications systems. It allows the user to input various system parameters and then computes the waiting time, i.e., the time from initiation of the message until it is transferred with a specified probability of correct message receipt. The waiting time is a function of frequency, transmitter, and receiver characteristics, antenna gain patterns, system protocol, distance separation, time of year and day, and other parameters. It is implemented on a minicomputer operated by the Institute for Telecommunication Sciences. Model users may remotely access the computer from their own terminals over telephone lines.

This model has been implemented on NOSC computers, modified to accept externally generated antenna pattern data, and used to compute MBCS performance for various types of antenna configurations.

4.1 ANTENNA PATTERN EFFECT

The apparent elevation angle α of a meteor trail at distance D from the observer is shown in figure 4.1 for various values of meteor trail height. Most meteor trails occur in the 80- to 120-km height range with the maximum occurrence at 100 km. The plan view of relative spatial distribution of meteor trail presence (product of occurrence and endurance) between two stations separated by 1000 km is shown in figure 4.2 by the closed contours. Superimposed are arcs of circles centered on the transmitter (T) and receiver (R) showing antenna elevation angles associated with the spatial distribution of meteor trails assumed to be at 100 km height. The "hot spots" of meteor connectivity, where the "100" contour is located, is illuminated by the two antenna at elevation angles of 9° to 10°. If the antenna on each end of the line was a vertical dipole 5 meters above the ground plane, its pattern maximum at 5° elevation angle, shown in figure 3.2(b), at one end would illuminate the same meteors seen at the other end at about 16° where a pattern minima occurs.

The MBCS link performance will be the sum of contributions from each elemental area of the meteor region which are in turn affected by the meteor rate and the associated effective antenna gains. Haakinson's model includes this integration which was first used by Heritage et al., (reference 25) to compute nuclear absorption effects of MBCS.

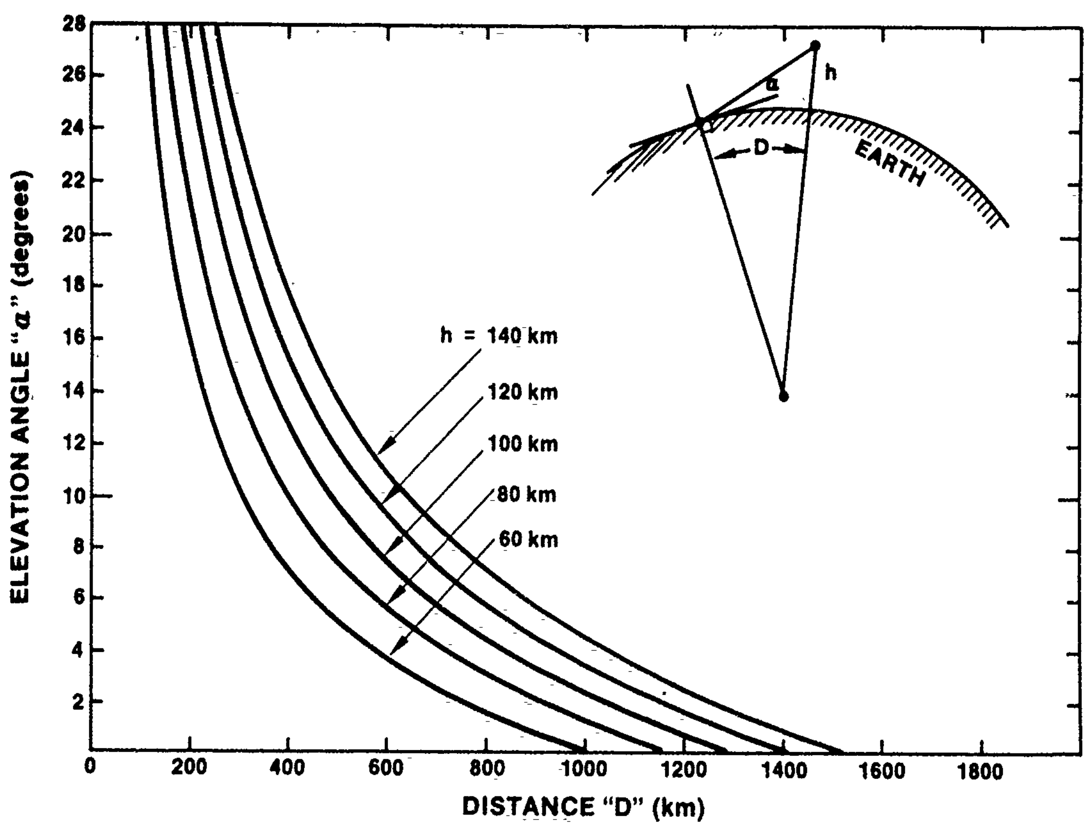


Figure 4.1. Plot of elevation angle α vs distance to point on earth below the meteor trail.

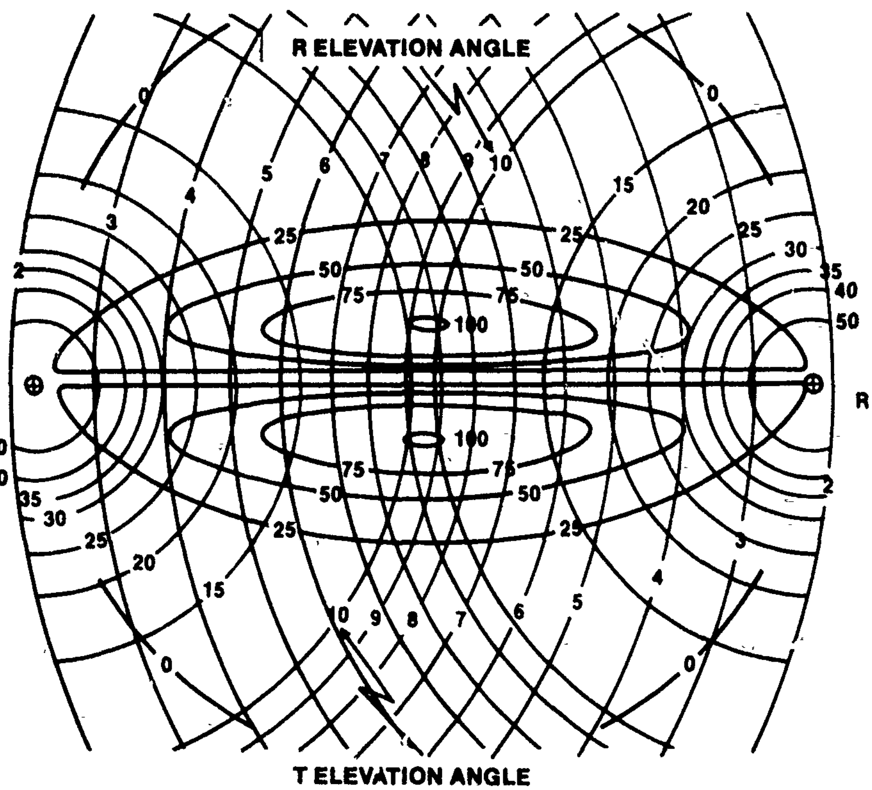


Figure 4.2. Spatial distribution of the total relative duty cycle of meteor trail reflections and elevation angles at which these trails are "seen" by antennas at each end of a 1000 km MBCS link.

4.2 MBCS PARAMETERS ASSUMED

MBCS link waiting time performance predictions have been made for both vertically and horizontally polarized antenna systems at various heights ranging from 10 to 40 feet. An 8-dBi vertically polarized yagi at the master station is assumed with each of the remote station antenna types (i.e., the vertical dipole, vertical 2-element collinear dipole array, and another vertical 8-dBi yagi). Calculations are also made assuming a horizontally polarized 8-dBi yagi at the master station and a horizontal crossed dipole and a horizontally yagi at the remote site. A smooth sea surface is assumed for the ground plane of each of the antennas. Other parameters assumed are listed in table 4.1.

4.3 PERFORMANCE VS ANTENNA HEIGHT AND TYPE

Figure 4.3 shows the results of waiting time calculations vs range assuming a vertical yagi with its center 20 feet high at the master station and a vertical dipole with its center at heights of 10, 20, 30,and 40 feet on the buoy. The ground wave range is not indicated. Measured data indicate the ground wave provides continuous coverage to about 200 nautical miles.

Table 4.1. Input parameters assumed for meteor burst communications system performance calculations.

	Remote	Master
Frequency	46.9	49.9 MHz
Transmit Power	24.8	30.0 dBw
Transmit Line Losses	1.0	1.0 dB
Antenna Circuit Losses	0.0	0.0 dB
Receive Line Losses	3.0	3.0 dB
IF Bandwidth	2.0	2.0 kHz
Required Predetection S/N Ratio	6.0	6.0 dB
Location Noise	Quiet Rural	Quiet Rural
Message Transfer	Multiple Burst Mode	Multiple Burst Mode
Message Length	100 msec	100 msec
System Overhead Per Burst	40 msec	40 msec
Month	May	May
Time of Day, Local	0600	0600

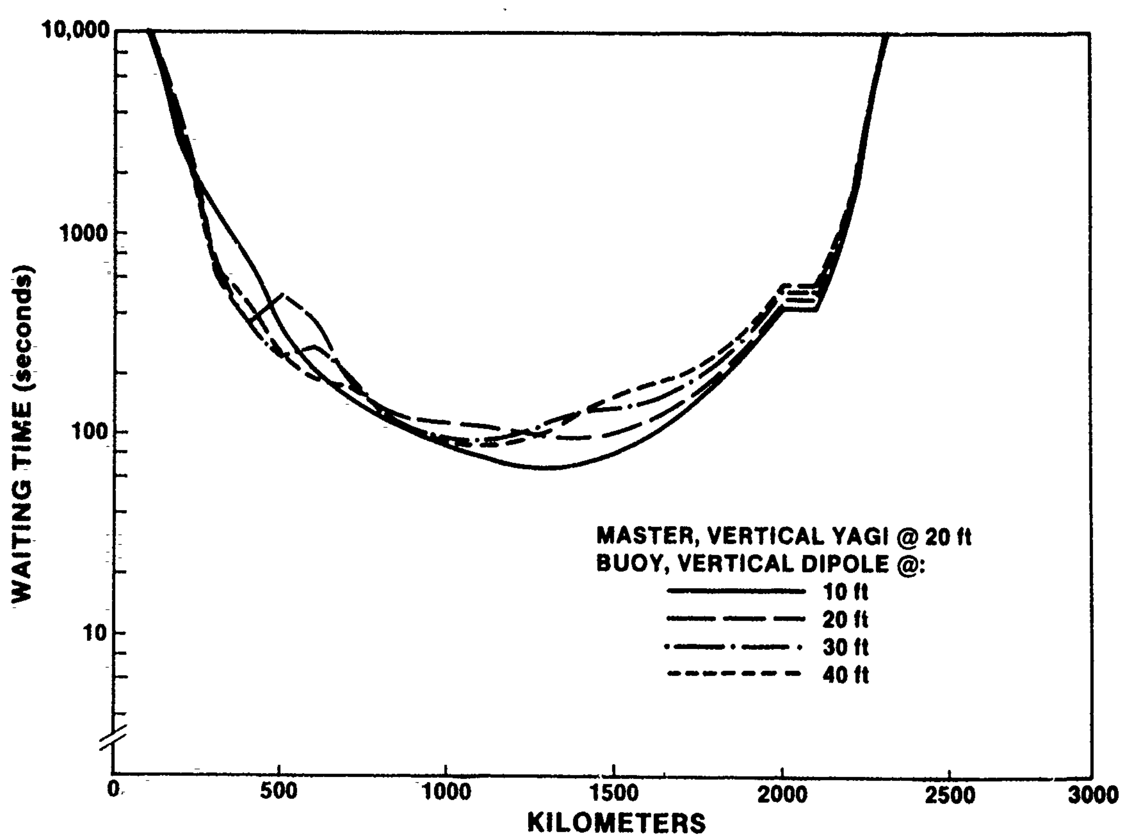


Figure 4.3. Computed message waiting time vs link distance for vertical dipole antennas on the buoy at various heights.

At the greater ranges beyond 100 km, the waiting time is generally less with the lower remote site antenna. In fact the best performance obtained was with the master station yagi also at 10 feet. Between the ground wave range and 700 km, the higher dipole antenna provides improved performance.

Waiting time calculations with the vertical collinear dipole array (figure 3.1(c)) at the buoy is shown in figure 4.4. The height indicated is the height of the center of the lower of the two dipoles.

Again, as with the single dipole, performance is better for the lower antenna heights at the greater ranges, but within about 1200 km, the 40 feet height provides better performance.

The results for the horizontally polarized antennas with an 8-dBi yagi 40 feet high at the master station and crossed dipoles at the buoy (figure 4.5) indicate the higher crossed dipole antennas gives better performance except within about 800 km range where the lower antenna is a little better.

A comparison of waiting time performance for the various types of antennas is made in figure 4.6. The curve associated with the optimum buoy antenna height for the long ranges in each of figures 4.3, 4.4, and 4.5 is reproduced in figure 4.6. At the longer ranges, the vertical collinear dipole array excells, with the horizontally polarized antenna system being the worst. However, the higher horizontally polarized antennas are the best at range within 1300 km.

Also shown in figure 4.6 is the expected performance improvement when a vertical 8-dBi yagi with its center positioned at 10 feet height is used at the buoy. Such an antenna has approximately the same height and azimuthal angles gain variations as the dipole within the useful azimuthal and vertical angles subtended by the meteor region. Therefore, as one may expect, the variation of performance vs range for the yagi is the same as for the dipole, with the yagi providing 1/2 the waiting time values. This is consistent with the 6-dB gain advantage of the 8-dBi yagi over the 2-dBi dipole. Additional improvement in performance for all vertically polarized antennas is obtained if the master station yagi is lowered from 20 feet to 10 feet. Table 4.2 tabulates these results.

Table 4.2. Comparison of waiting time in seconds for various antenna types.

Buoy Antenna	Height (feet)	Range (km) 700	1300	1900
Vertical Dipole	10	122	66	243
Vertical Collinear Dipole	10	108	59	185
Vertical Yagi	10	74	33	120
Horizontal Crossed Dipoles	40	100	60	626

NOTE — Master Station uses:

1. 20 foot high vertical yagi with all vertically polarized buoy antennas
2. 40 foot horizontal yagi with the horizontal crossed dipole antenna on the buoy.

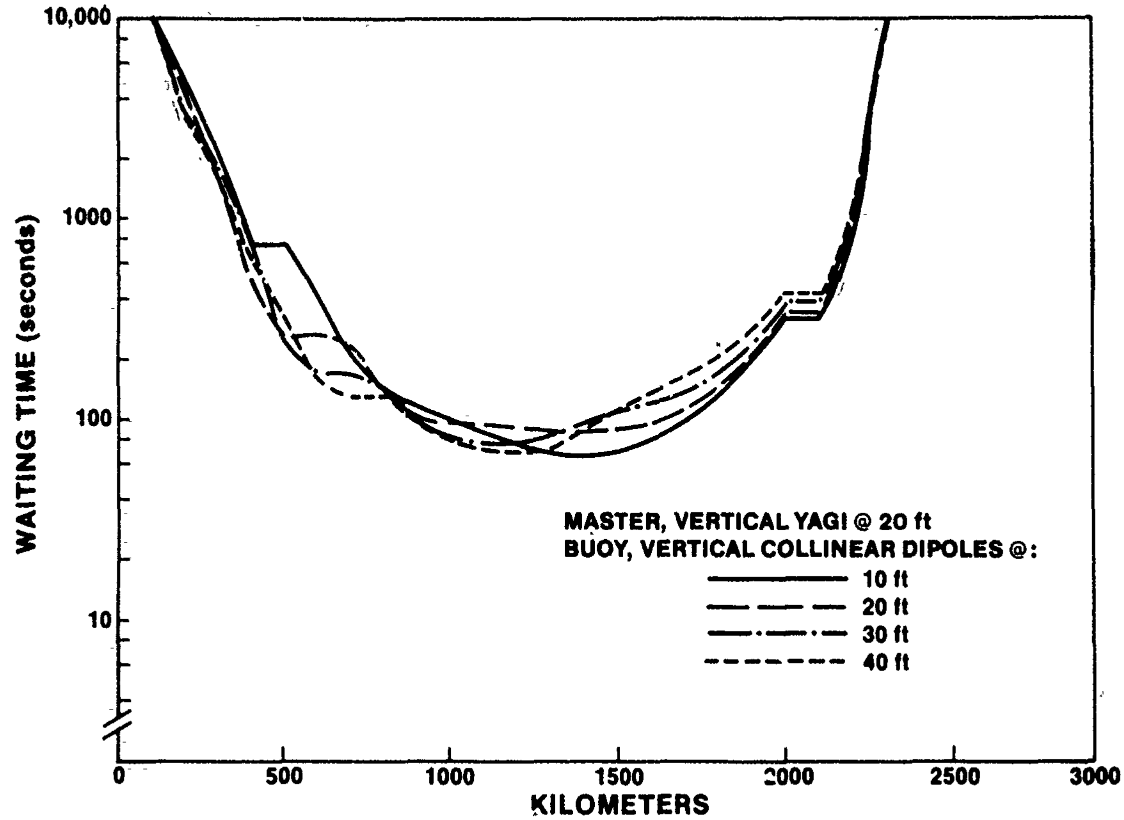


Figure 4.4. Computed MBCS message waiting time vs link distance for two vertical collinear dipoles on the buoy at various heights.

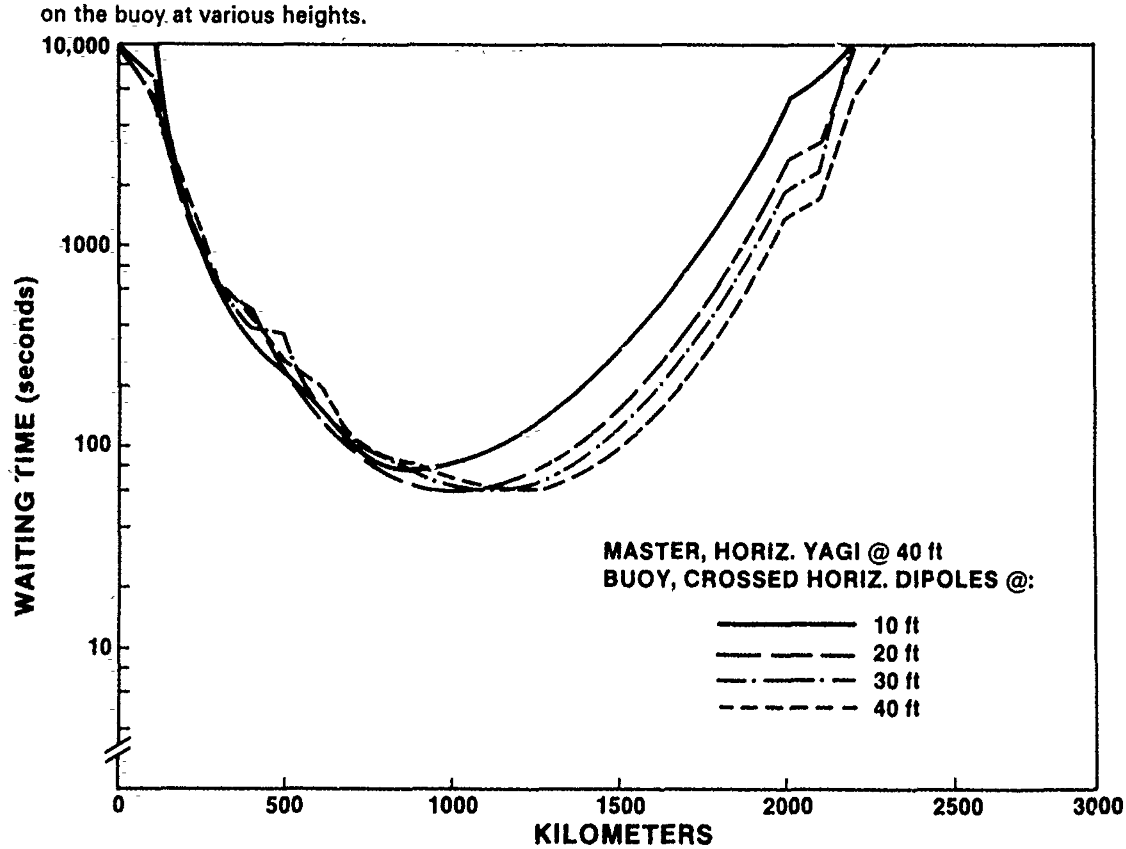


Figure 4.5. Computed MBCS message waiting time vs link distance for horizontal crossed dipoles on the buoy at various heights.

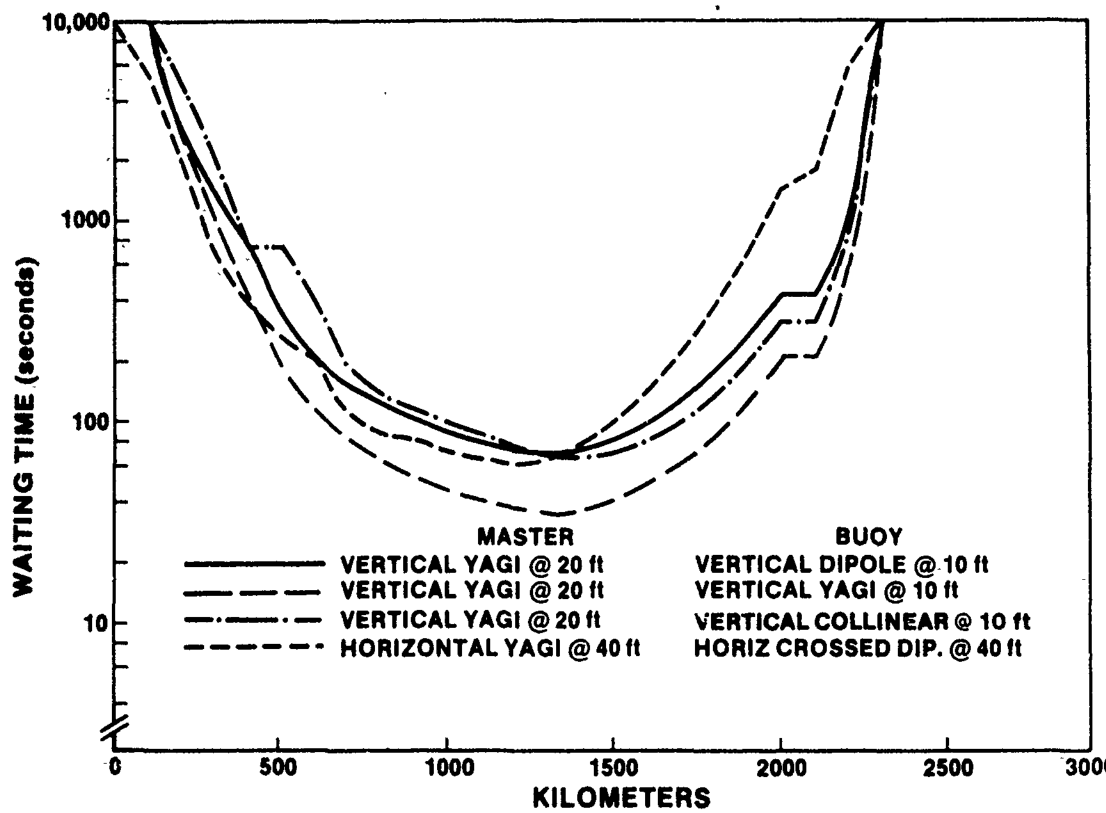


Figure 4.6. Computed MBCS message waiting time vs link distance for various vertically and horizontally polarized antennas at their optimum operating heights.

4.4 OPTIMUM BUOY ANTENNA SELECTION

The results presented above for omnidirectional remote station antennas clearly indicate that when seawater is the antenna ground plane the vertically polarized antennas assumed at low heights provide improved performance beyond about 1300 km. Horizontally polarized antennas perform better with increasing height, but even the 40 foot height did not perform nearly as well as the vertically polarized antennas. At shorter ranges, the horizontally polarized antenna performs a little better, even for its lower heights. Thus, it appears the optimum antenna type is a function of the application.

Generally, for the buoy application where maximum range is desirable, it appears the vertical dipole is the best choice in that the lower height and thus smaller size of the antenna will

1. minimize storage and deployment problems

2. minimize wind drag and moment arm forces on the buoy when it is swaying in rough seas thus allowing perhaps for a generally smaller buoy for support

3. minimize the radar cross section to maximize its covertness and reduce possibility of being tampered with or destroyed.

Horizontally polarized antennas may be required where the buoy relay system is to support a land-based system employing a horizontally polarized antenna to optimize its land links. They may be desirable where shorter ranges only are to be supported and the higher antennas are acceptable on the buoy.

5.0 POWER SOURCES

For this study a broad survey was made of known power sources. The survey addressed

1. power sources that are available as off-the-shelf products or only require engineering for a specific application

2. feasible power sources under development that are in the near-term reachable stage that offer significant advantages over currently available sources in terms of endurance, energy density, cost savings, or ease of deployment.

Also of particular interest are power sources that do not require, or minimize the use of, critical materials such as silver and platinum and potential pollutants such as mercury. Power sources with development well into the future (such as nuclear fusion) or which are not appropriate to this application (such as manpower or marine mammals) are not included.

A tremendous number of devices and physical phenomena appear useful in ocean power systems as indicated by figure 5.1. A wide variety of systems – mechanical, thermal, chemical, electrical, radiant, and nuclear – are available to satisfy the complexity and scope of future requirements. The extensive survey reported in reference 26 is summarized and updated in this section.

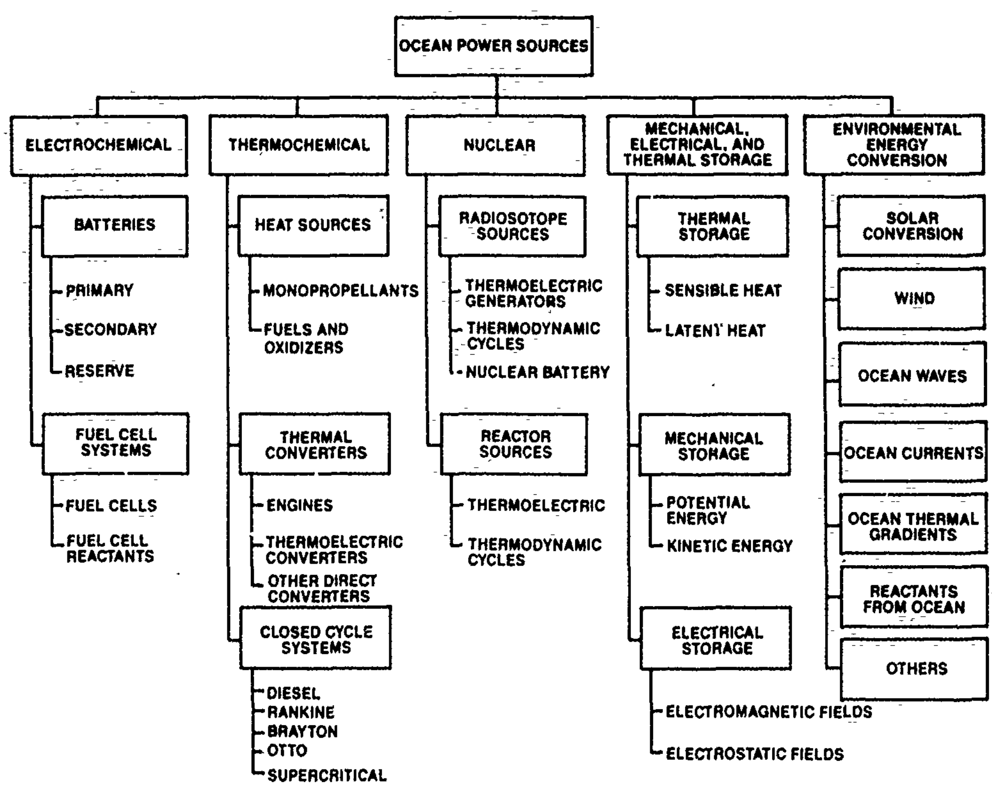


Figure 5.1. Structure of current power source technology for ocean applications.

5.1 SELECTION CRITERIA

Weight is a figure of merit popularly used to compare systems. A realistic weight estimate must include items such as power conditioning or voltage regulation requirements imposed on the electronic equipment, and other factors not usually included in a preliminary weight analysis.

One difficulty in evaluating systems lies in the fact that the usefulness of energy conversion phenomenon is dependent on new, constantly changing material parameters and device fabrication techniques. This is a direct consequence of the almost exponential characteristic growth of research and development. The projection of system performance, consequently, always contains a degree of uncertainty.

Keeping in mind these limitations, the results presented here establish the types of buoy missions where a specific system might be useful, the approximate weights of these systems, empirical and analytical relationships describing their performance, and other characteristics of interest.

5.2 ENERGY SOURCES

Energy exists in a number of forms and may be thought of as stored energy or energy in transition. Many energy conversion systems are known for transforming energy from one form to another as shown in table 5.1. Some of these have been developed into practical state-of-the-art systems or are considered feasible for practical use and are currently in various stages of development.

A power source consists typically of an energy conversion system for converting the stored energy into a form usable for the desired application. The power source may or may not also include the energy source, depending on whether the stored energy is furnished with the energy conversion system (either integrally as in a battery or separately as in the fuel for a heat engine) or whether the stored energy is extracted from the environment (for example, chemical energy by an air-breathing heat engine or kinetic energy by a windmill).

For communication applications the desired output of the power source is electrical current. Energy conversion from the stored energy to the electrical output may be in one step, as in the stored chemical energy of a battery being converted to electrical energy by galvanic action, or in two or several steps, as in a diesel generator where the stored energy of the fuel and oxidizer are converted from chemical to thermal to mechanical to electrical energy.

The high-energy content of some chemical fuels makes it possible to store energy source material for oceanic missions. The use of thermal storage is promising for short-term missions where the simplicity of an available heat source is of value. The use of environmental energy sources makes it possible to have indefinite endurance, but the power densities are low and the availability (e.g., solar energy) may not be predictable. Nuclear sources offer very high energy content and long life at a penalty of very high initial cost.

Table 5.1. Energy conversion systems.

Converters	Type of Change	Energy Source	Energy in Material Taken to Site: Electro-chemical	Thermo-chemical	Nuclear	Stored Thermal	Stored Mechanical	Stored Electrical	Energy Extracted from Environment at Site: Solar	Thermal Gradient in Ocean	Kinetic (wind, wave, currents)	Gravity	Chemical (e.g., of oxygen in air)
Direct Energy	Chemical to Electrical	Primary batteries	X										X
		Secondary batteries	X										X
		Fuel cells	X										X
	Thermal to Electrical	Thermoelectric gen.		X	X	X			X				X
		Thermoionic gen.		X	X	X			X				X
		Magneto-hydrodynamic devices, Electro Fluid, Dynamic converters, etc.		X	X				X				X
	Radiation to Elect.	Photovoltaic cells		X	X				X				
		Nuclear batteries			X								
	Elect. to Electrical	Inductors						X					
		Capacitors						X					
Dynamic Energy	Thermal to Mechanical	Diesel engines		X								X	
		Otto engines		X								X	
		Rankine engines and turbines		X	X	X		X	X			X	
		Brayton turbines		X	X	X						X	
		Stirling engines		X	X	X		X	X				
	Mechanical to Mechan. (kinetic to kinetic)	Flywheels					X						
		Windmills									X		
		Wave/current generators									X		
	Mechanical to Mechan. (potential to kinetic)	Springs					X						
		Compressed gas					X						
		Pressure-actuated devices										X	
		Falling weights										X	
		Buoyancy devices										X	
	Mechanical to Electrical	Electromagnetic gen.									X		
		Piezoelectric gen.									X		
		Electrostatic gen.									X		

5.3 ENERGY CONVERSION

Highly efficient electrochemical conversion devices, such as batteries and fuel cells, make the best use of the energy available in chemical sources. Unfortunately, many of the chemical batteries have relatively low energy density chemical reactions which do not allow them to approach the performance of the hydrogen-oxygen fuel cells on a long-lived mission. It is important to note, however, that there are various types of lithium batteries presently being developed that have energy densities equal to fuel cell power systems. It is expected that these lithium batteries will be available for general use within the next few years at a cost comparable to conventional batteries on a dollar/watt-hour basis.

Thermoelectric devices are relatively inefficient, but provide long-lived static conversion which is applicable to low total energy missions. The thermoionic converter with its simple system design is substantially more efficient than the thermoelectric converter, but it is not completely developed. Magneto-Hydrodynamic (MHD) converters have promise of very high conversion efficiency with very high temperature heat sources, but development is still in early stages. While photovoltaic devices are obviously limited by the combination of weather and diurnal cycles, they may be applicable when small power levels are needed for very long times. Rotating machinery systems will probably continue to dominate the high-power region for most applications. Typically a nuclear steam cycle of thermoelectric conversion may be applicable to in-situ power generation, while a tethered buoy with diesel or gas turbine conversion and submerged fuel storage may be used where air umbilical is permissible.

5.4 POWER SOURCE SELECTION

Surface power systems are those that are located on the sea surface or have ready access to the surface (such as snorkeling diesel engine) for the intake of air and emission of by-products, are free from high hydrostatic pressure, and have ready access for maintenance and replenishment.

As shown in table 5.2 many combinations of energy sources and energy conversion systems can be considered for surface power systems. Where the power requirements are low (in the 1- to 10-watt range) and endurance is less than a few years, batteries are usually the most economical and reliable power source. The most extensively used battery power supply for marine applications is the air-depolarized battery, which is used by the U.S. Coast Guard in aid-to-navigation buoys. These batteries have been used in thousands of buoys for the past 10 years. They provide up to 3 years of service between replacement when powering high efficiency light flashing devices that are photoelectrically controlled.

Experience with other power systems in the marine environment is with few exceptions, quite limited. This includes several types of primary batteries, metal-air batteries, hydrogen-air fuel cells, chemically fueled thermoelectric generators, photovoltaic cells, diesel generators, wind-powered converters, and water-wave-powered generators. Each of these is described as a possible candidate in a summary format.

A quantitative evaluation of advanced power systems for communication systems is presently possible provided the analyst is willing to accept a certain accuracy bandwidth or tolerance centered about the final result.

Table 5.2. Power sources for surface applications.

Direct Energy Converters	
Batteries	Primary
	Secondary
Fuel cells	Hydrogen-oxygen
	Alcohol
	Hydrazine
	Ammonia
	Hydrocarbon
	Solid reactants
Thermoelectric generators	Chemically or nuclear fueled
Photovoltaic cells	
Dynamic Energy Converters	
Heat engines	Diesel
	Otto
	Rankine
	Brayton
	Stirling
	Heat sources for heat engines
Environmental kinetic energy conversion	Wind-powered generator
	Water-wave-powered generator
	Air pressure barometric generator
	Ocean-current-driven generator
Gravitational energy converters	Hydrostatic pressure differential
	Falling weights
Stored mechanical energy converters	Kinetic, flywheel
	Strain energy, springs
	Strain energy, compressed gas
	Phase change, liquid-to-gas

The primary screening procedure was performed by organizing the power sources according to the availability of the source technology as shown in the following table:

Availability	Power Source
Readily available or on the shelf (available within one year)	Primary batteries Storage batteries Metal-air cells Engine generators Gas-fired thermoelectric generators Cables to shore or to sea floor sources
Requires minor development (available within one to three years)	Wind generator Wave generator Solar generator Air fuel cells Liquid fueled thermoelectric generators Fossil fueled turbine generators Metal-air fuel cells NOSC seawater battery (appendix B)

5.5 PARAMETRIC DATA FOR POWER SOURCES

A computer program was used to generate a large, comprehensive parametric data base for the numerous, currently available and applicable power source candidates (reference 26). Individual cases were computed for the power source candidates based on these requirements:

1. locations above the sea surface
2. power levels of 1, 10, 100, and 1000 watts
3. endurance of periods of 1 month, 3 months or, 6 months.

Tables listing the power sources for each case considered are found in appendix A. A power source identification number is shown in parentheses following the name of each of the power sources. This identification number correlates with an identification number given in the descriptive data sheets presented in reference 26 and in appendix C.

The output listing shown in appendix A presents the candidate sources in the order of increasing cost, with the lowest cost source listed first. These cost values should be considered as "relative values" and are based on 1975 cost data. Newer technologies are not included in this appendix except that the NOSC seawater battery is discussed in appendix B. Each source's cost, weight in air, and volume are calculated for the requirements of each particular case. The right hand column identifies critical or hazardous materials, if any, and any special requirements such as maintenance intervals or energy storage systems.

Using the parametric data as a basis, figure 5.2 displays the best power source candidates for an ocean surface mission, according to least cost, least weight, and least volume, in chart form.

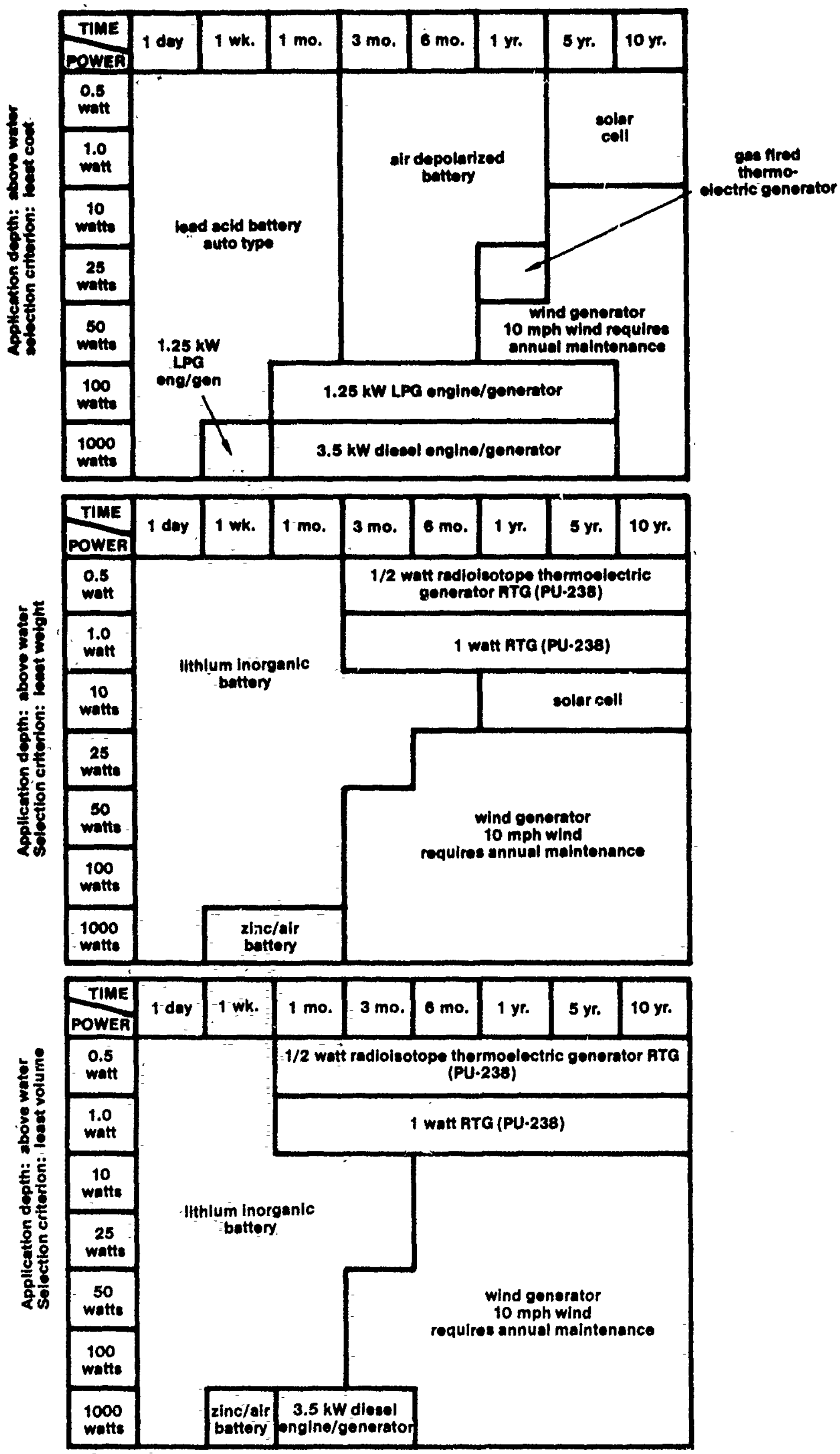


Figure 5.2. Optimum energy source candidates for an ocean surface mission, according to least cost, least weight, and least volume.

5.6 RECOMMENDED POWER SOURCES

Selections of suitable power sources for the MBCS buoy relay have been made, in part from the guidance provided by the parametric data presented in appendix A. In addition, newly available and soon-to-be available technologies have been considered, and updated cost analysis used in order to make these selections. Table 5.3 shows these selected power source candidates and provides characteristics of these power sources for three selected focal applications identified as missions 1, 2, and 3. The major distinction between these missions, as it may affect the power source, is the varying duty cycle that the transmitter is required to provide. The duty cycle requirements for various missions were discused in detail in section 2.0 above.

The selected sources are grouped under present technology and advanced technology in table 5.3. Weights, volumes, and cost are provided for each candidate with respect to the discrete focal missions. Comments are provided pertaining to risk, development cost, and the need of a rechargeable storage battery to be used with certain prime energy sources. In addition, figure 5.3 displays specific energies and energy densities for these candidates.

The recommended selections based on minimal cost for each mission and based on minimal size and weight for each mission are indicated. Hydrogen-oxygen fuel cells have not been recommended due to lack of experience in oceanic missions. Power sources that require a conversion of naturally available energy such as wind, waves, ocean currents, thermal gradients, and solar radiation have not been considered because of the unpredictable environment where they may be deployed, resulting in a lack of reliability. In addition, these power sources are generally not applicable to the short mission intervals that are being considered, due to cost considerations. Similarly, nuclear sources have not been recommended because of the short mission intervals.

Recommended power sources include

1. Present Technology

- Alkaline batteries are made up of several alkaline zinc carbon lantern cells. These are readily available sources as described in appendix C, section 1.1.2.

- Lithium batteries are today available in large, multicell form and are described in appendix C, section 1.1.3.

- Zinc air cells are readily available, commonly used in buoys, and are described in appendix C, section 1.1.11.

- Gas-fired thermoelectric generators have been extensively used and are described in appendix C, section 2.1.1.

2. Advanced Technology

- Diesel-fired thermoelectric generators are being developed under the U.S. Army liquid fueled thermoelectric generator program as described in reference 27. It is possible to burn a variety of liquid fuels including diesel, JP-4, gasoline, kerosene, and heating oil with a recently developed ultrasonic combustion atomizer.

Table 5.3. Summary of selected power source candidates.

MISSION	1	2	3	REMARKS
Receiver/Processor	0.7 W	0.7 W	0.7 W	
Transmitter Demand	620 W	620 W	620 W	
Average Power	1 W	100 W	300 W	
Duration Energy	90 Days	90 Days	90 Days	
Energy	2160 WH	216 kWH	648 kWH	
WEIGHT/VOLUME/COSTS	(lbs/ft^3/\$k)	(lbs/ft^3/\$k)	(lbs/ft^3/\$k)	
PRESENT TECHNOLOGY				
Alkaline Cells	62/0.58/0.14[1]	6200/58/14	18,500/175/41	Lowest risk
Lithium Cells	11/0.13/0.4[2]	1100/13/40[2]	3300/40/120[2]	Safety restrictions
Zinc Air Cells	50/0.50/0.2	2700/37/4[1]	8100/110/12[1]	Nicad required, air intake
Gas-Fired Thermoelectric Generators	NA	1500/40/8	5000/110/20	Nicad required, propane storage, air and exhaust
ADVANCED TECHNOLOGY				
Diesel-Fired Thermoelectric Generators	NA	1900/40/10	6500/140/23	Nicad required, diesel storage, air and exhaust, $0.5 M R&D required
Alum Air Fuel Cells	NA	1100/40/10	2000/90/18	$2 M R&D required air intake
Gas-Fired Turbine Generators	NA	370/25/20	800/30/25[2]	$1 M R&D required, Nicad required, air and exhaust, propane storage
Seawater	0/0.10/0.5[1,2]	500/10/3[1,2]	1500/30/10[1]	$0.5 M R&D required, Nicad required, large area cathode

NOTES:

1. Recommended selections based on minimal cost.
2. Recommended selection based on minimal size and weight.

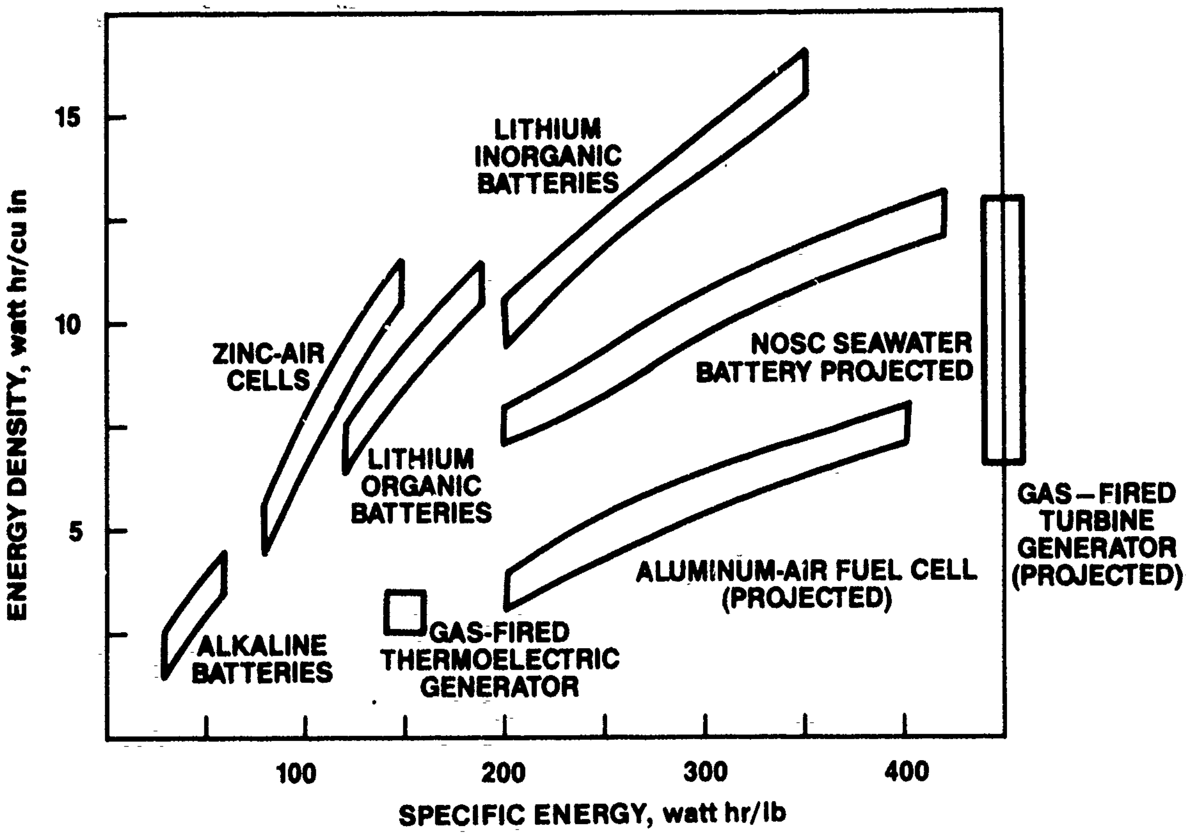


Figure 5.3. Specific energy and energy density of selected energy source candidates for the MBCS.

- Aluminum air fuel cells are being developed by the Department of Energy for electric automobiles. A variation of the aluminum air battery has been proposed for missions 2 and 3.

- Gas-fired turbine generators have been developed for a variety of terrestrial and space applications as described in reference 28. The major advantage with these sources is reduced fuel consumption compared with the less efficient thermoelectric conversion.

- The NOSC Seawater Battery has been under development for near surface and deep ocean applications in the 1- to 10-watt range. These sources could be developed for the multihundred watt power range as more advanced field effect transistor switches are made available. A description of the NOSC battery is provided in appendix B.

6.0 BUOY SYSTEM DESIGNS

6.1 INTRODUCTION

Each MBCS relay station will occupy a buoy which rides on the surface of the ocean. There are necessarily a variety of sizes and configurations of these buoys and their peripheral components in order to satisfy the range of missions. Factors which cause these variations include

1. the size and shape of the antenna,
2. the weight and volume of the energy source and whether it requires ventilation,
3. whether the system must be anchored or connected to a drogue,
4. the range of environments throughout which the system must perform satisfactorily,
5. how the system will be deployed and (possibly) serviced, and
6. how long the system must survive at sea in the standby and operational modes.

6.2 GENERAL DESIGN CONSIDERATIONS AND CONSTRAINTS

6.2.1 Environment

The design goals for most of the stations are for them to be capable of remaining afloat in the environment accompanying a sea state 8 and to give a creditable performance in sea states 0 through 6. A sea state 8 is characterized by average wave heights of 25 to 40 feet and with winds as great as 47 knots. A sea state 6 has average wave heights from 8 to 12 feet with winds as great as 28 knots. For most of these buoy systems a "creditable performance" means that the antenna will be held in a position which will enable the station to communicate at least 90 percent of the time that suitable meteor trails exist. A relaxation of the rough-water performance requirement may be allowed as a necessary compromise for a very small remote station.

6.2.2 Station Keeping Requirements

The value of an MBCS buoy for servicing other stations within the network will diminish as it drifts away from the operating area. Surface currents throughout the ocean areas vary considerably as a function of time and location. Overall sets (drifts) in a particular direction are likely to average 3 to 15 nmi per day, but they may far exceed 24 nmi in unusual cases. See figure 6.1 for typical drift patterns in the Pacific based upon average surface currents. A buoy system may be driven yet farther off position by winds acting directly on its superstructure. Several methods are discussed in section 6.4 for limiting the distance or rate that a buoyed station will drift.

6.2.3 Antenna Requirements

The antennas must vary in size, shape, and stowability as dictated by the radiation characteristics of section 3.0, the related performance considerations of section 4.0 and the constraints of the available deployment methods. Antenna structures of two radically different sizes and shapes appear to satisfy most of the requirements for communications paths

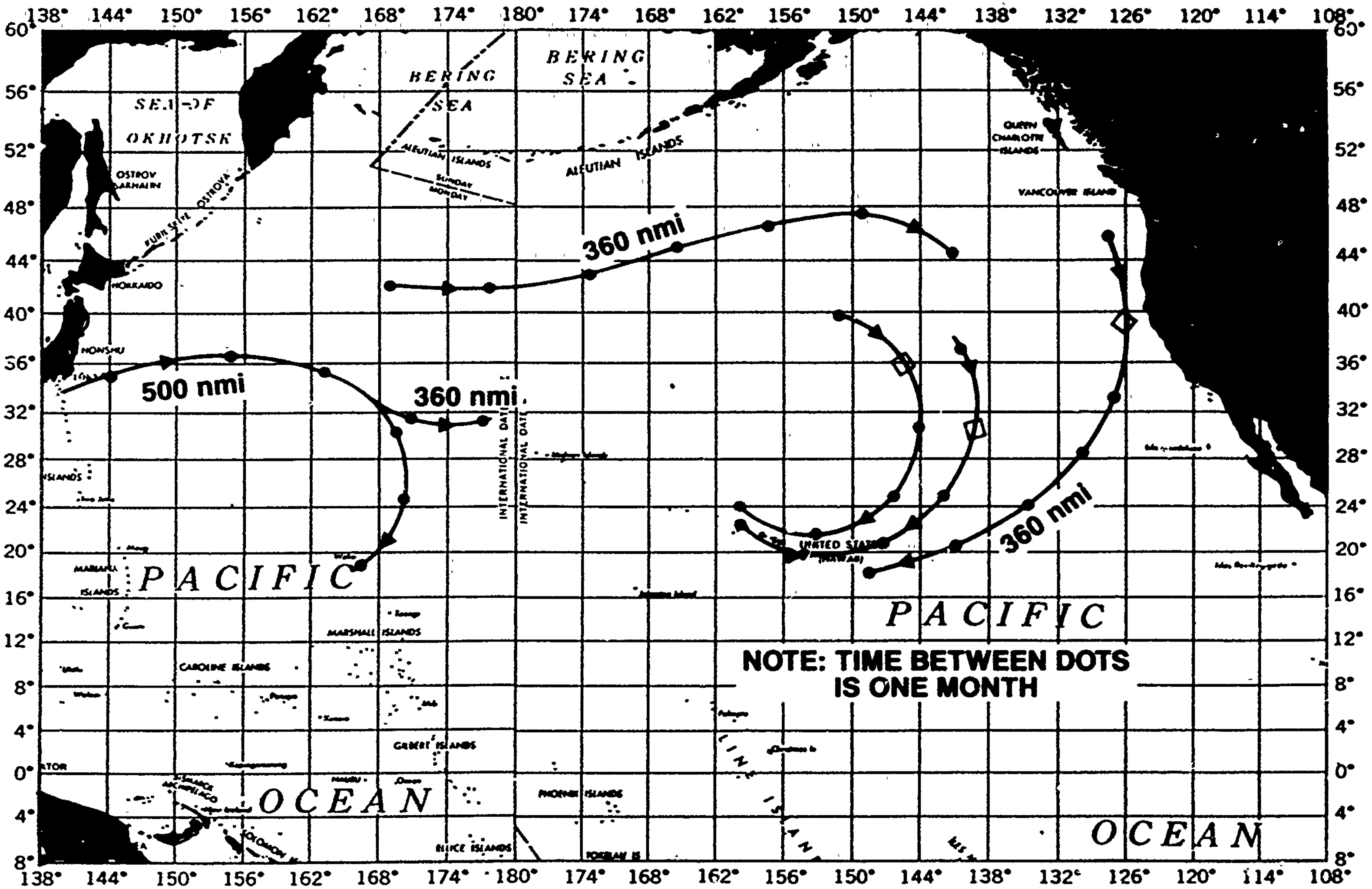


Figure 6.1. Examples of buoy drifts for average surface currents. The nmi notation near the drift tracts is the drift distance per month (between marks).

in the first 20 degrees above the horizon. The smaller structure is a vertical whip which is used for communicating with vertically polarized stations. The vertical whip imposes no special demand on the buoy design. An effective whip at 48 MHz is only 14.8 feet tall (see figure 3.1 (b)). The larger structure is used for horizontally-polarized communications. It must support a pair of horizontally-crossed dipoles about 40 feet above the ocean surface (see figures 3.1 (h, i)). This calls for a larger supporting buoy, a heavier ballast weight and the attendant problems of deploying a larger system and somehow keeping it covert (i.e., hidden from enemy radar and optics).

6.2.4 Energy Source Requirements

The size, shape, and special fixtures of the buoys must vary so as to accommodate an appropriate energy source for the particular objective. This is illustrated by the following hypothetical station examples which are basd on reasonable missions and the energy supply recommendations of section 5.

Example #1 consists of a small MBCS relay station whose mission is described in section 2.1. This station requires only 1944 Wh (watthour) of energy over a 90 day operating period during which it generally draws 0.7 W while receiving and 620 W while transmitting (transmissions total one hour). This wide range of power demands can be satisfied by a nickel-cadmium battery which is continually charged at an average rate of 1 W from a 100-pound alkaline battery suspended 40 feet below the buoy. In this position the alkaline battery and its pressure-tight container also serve as a ballast weight. This battery is a little oversized so that its potential energy of 3000 Wh provides a safety margin over the estimated requirement. The buoy portion, being essentially a half-submerged 3-feet diameter sphere, displaces 450 pounds.

Example #2 consists of a larger station whose mission is described in section 2.3. This station is assigned the role of transmitting on a 16-percent duty cycle for 90 days. The input power requirements are 620 W while transmitting and 0.7 W at all other times. The resulting total of nearly 215 kWh requires a large energy source. A 1100-pound battery of lithium cells is ruled out for its high cost ($40,000) and its safety restrictions. (Most lithium chemistry batteries are not allowed to be operated aboard ships and aircraft because of their history of exploding under certain circumstances). An alternate battery is composed of zinc-air cells at about 10 percent of the cost of the lithium counterpart, but this zinc-air battery weighs about 2700 pounds and is complicated by the need for intake and exhaust manifolds and suitable snorkels for excluding seawater. The resulting station must displace about 5000 pounds. Hence, the increased transmitter duty cycle has resulted in a station which is ten times the size of the station in example #1.

Example #3 consists of a large anchored station that consumes an average power of 300 W because of its numerous high-power transmissions. The desire is to keep this station operating as long as a year by replenishing its energy supply every three months. The primary source of energy is a 100-gallon neoprene bag of fuel oil which is held 50 feet below the surface by means of a weight and is kept from sinking lower by means of a line which links the bag to a surface buoy. This surface buoy is fastened in that portion of the anchor line which extends 100 feet along the surface from the MBCS buoy before routing downwards from the final surface float which supports the anchor line. (See figure 6.9, which depicts this type of mooring). The hydrostatic pressure of the ocean forces the lower-density fuel from the bag and along a 1/4-inch (ID) flexible tube which links the bag to the MBCS buoy. Inside the buoy a 3.5-kw diesel engine/generator regulates the fuel flow while running for about 1 hour in 8 to recharge the adjacent nickel-cadmium battery. While this station is expected to draw 3 times the average power of the one in example #2 and perhaps 12 times the total energy, the displacement of the main buoy may be less, perhaps 4000 pounds, because the energy is stored elsewhere (i.e., in the bag and on shore).

6.2.5 Deployment/Repair/Recovery Considerations

The MBCS buoy relay stations must be designed for expeditious and reliable deployments. The difficulty ranges from the relative ease of setting a small, freely drifting station over the side of a ship, to the design challenge leading to the successful air deployment of a large station which must then proceed to anchor itself to the ocean floor at an uncertain, great depth. Intermediate difficulties will be encountered in designed air-dropped and submarine-launched stations which are not required to anchor.

A possible deployment sequence following ejection from a submarine torpedo tube is illustrated in figure 6.2. After the station package has reached the surface and its spherical bladder inflates, a portion separates and falls to the length of a 40-foot cable. There the combination battery/ballast weight stops, but the underwater communications device continues to descend to a depth of 300 feet. The antenna erects, the station turns on and reports its ready status over its acoustic link to the submarine's underwater telephone.

A deployment sequence involving an air dropped anchored buoy is described at the end of section 6.4.3

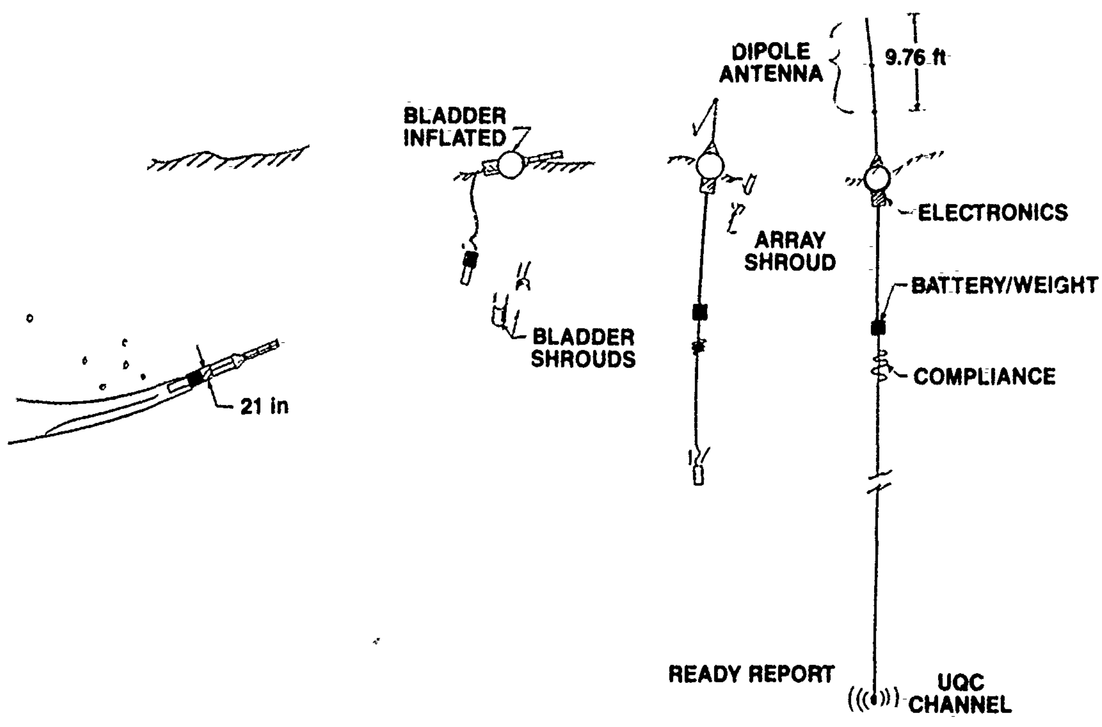


Figure 6.2. Deployment of a covert MBCS station from a submarine.

It is expected that some of the larger buoy stations will be recovered by sea-going tugs, oceanographic vessels and/or other ships having suitable manpower and hoisting equipment. Repairs may sometimes be accomplished on a floating station but, more likely, after it has been hoisted aboard or returned to shore.

6.2.6 Navigational Requirements

For peace-time operations of the MBCS buoys, their menace to navigation will be minimized through the use of lights, radar reflectors and color schemes in accordance with the International Rules and the Coast Guard Regulations. Each deployment and retrieval will be reported to *The Notice to Mariners*. None of the above will apply in a national emergency.

MBCS buoy networks will require a means of tracking their buoyed stations. Several options exist as long as navigational satellites continue to operate. A simple way is to install an ARGOS transmitter on the buoy. For a small expenditure of energy the ARGOS system will give a daily or weekly fix, as desired, with a resolution much finer than 1 nmi. Another way is to install a SATNAV receiver on the buoy and periodically report the position as a small addition to the normal flow of meteor-burst traffic. Yet another way is to determine the fixes from shore-based Omega transmissions and periodically report these results over the meteor burst link. In preparation for the time that all of the above navigational channels fail, the station could be outfitted with a 10-W VHF transmitter which responds to a coded interrogation signal by turning on for 20 seconds and reporting the station's identity. A high-flying aircraft could associate the station's identity with its bearings from the aircraft and, ultimately, the station's triangulated fix.

6.3 BUOY HULL SELECTIONS

In the following paragraphs the wide selection of buoy possibilities is narrowed to two types for the MBCS applications. One closely resembles a contemporary research buoy. The other combines the advantages of the first with attributes of a second, which has been in use for over two decades.

6.3.1 Surface-Slope-Following Buoys

Several of the numerous buoys of this class are the Bumblebee (reference 29), NOMAD (reference 30), Monster (reference 31), and variations of the toroidal buoy (reference 32) (see figure 6.3). They all have a common characteristic of maintaining their decks approximately parallel to the adjacent ocean surface. A double-gimbaled pendulous adjunct was considered for keeping the antenna upright while the buoy tilts in various directions, but the riding characteristics of other buoy classes offer easier solutions. For this reason surfacing-slope-following buoys were ruled out for this MBCS application.

6.3.2 Spar Buoys

The University of California's spar buoy FLIP (reference 33) (see figure 6.4) would be a most satisfactory design for supporting any of the antennas (section 3.0), power supplies (section 5.0), and all the other items which complement any MBCS sea station if it were not too large, too expensive, and too hard to conceal. FLIP has an overall height of

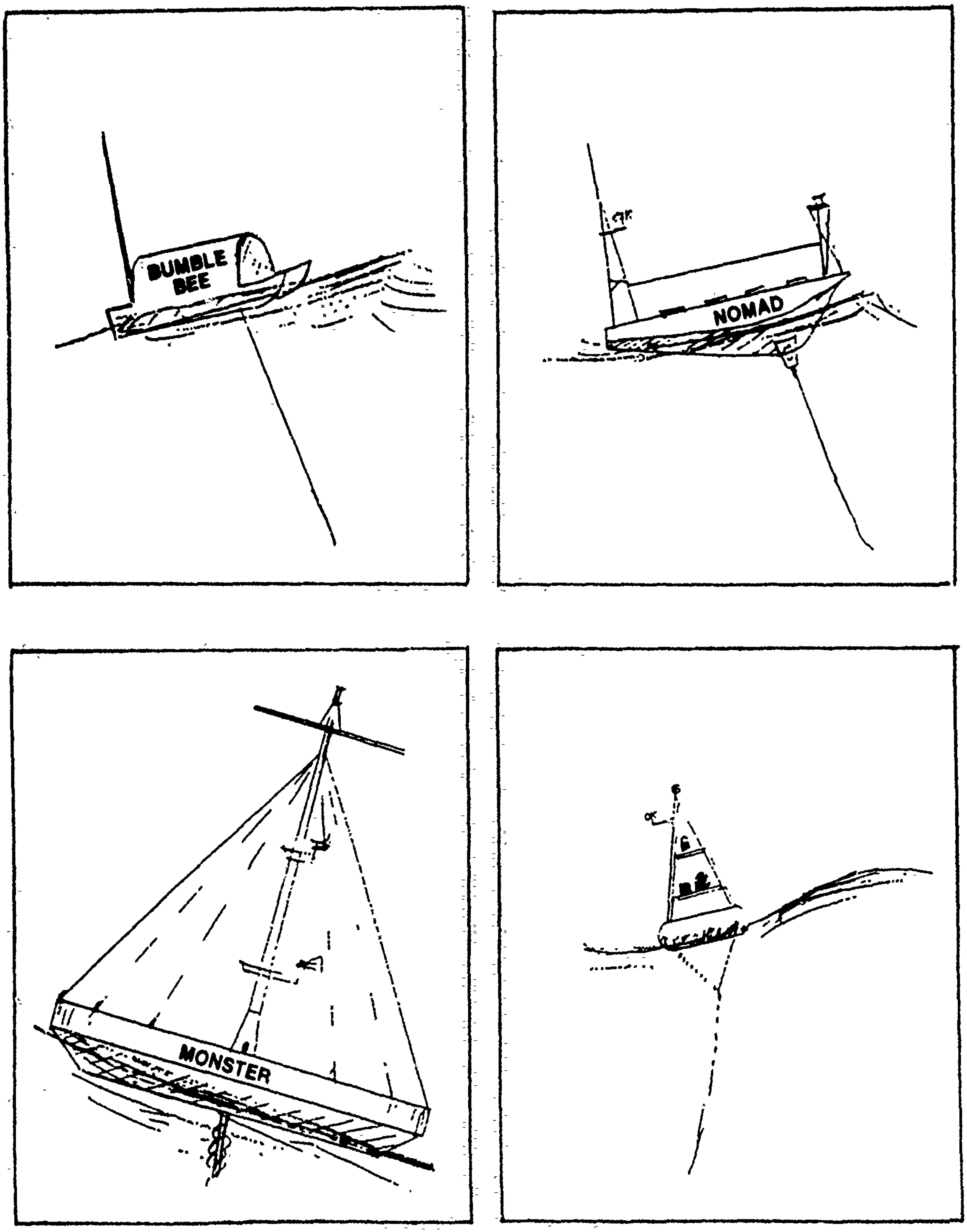


Figure 6.3. Surface-slope-following buoys.

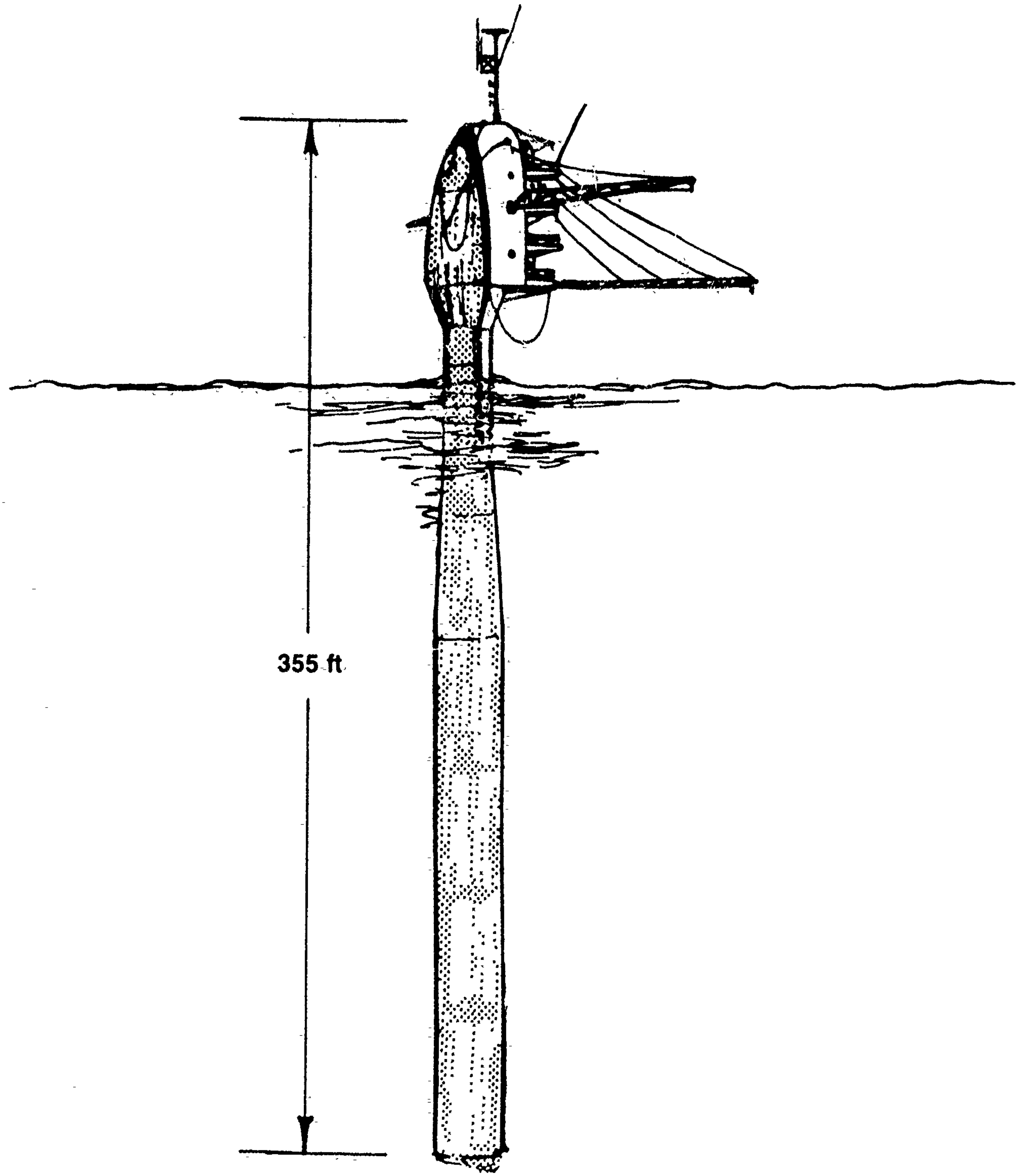


Figure 6.4. The FLIP buoy.

355 feet with about 60 feet (not counting antennas) extending above the average ocean surface. Even NOSC's spar buoy ISAR (figure 6.5) with its 70-foot length, not including its suspended damping plate, is still large enough to make deployment a problem even from a ship. Furthermore, spar buoys of the ISAR size and smaller often tilt too much in rough seas. ISAR has been observed to tilt 20 degrees in the long-fetch swells which accompanied a sea state 5 or 6 in the Pacific. The orbital currents within the waves and swells cause differential drag forces along the great vertical extents of these spar-shaped buoys. These generally result in force couples which periodically torque the buoys into excessive tilting attitudes. Such effects may be reduced for buoys of the type described in reference 34 (see figure 6.6), by centralizing most of the buoyancy in a short, submerged section from which a long, slender mast extends upward, well past the average ocean surface. But for survival in a sea state 8 or even a successful operation in a sea state 6, a buoy of this shape must be extremely tall and is at risk with its marginal reserve buoyancy. While this approach may yet have merit for some especially covert operations where reliability may be sacrificed, the attendant problems of spar buoys are presently ruling them out for this MBCS application.

6.3.3 Pendulous Spherical Buoys

Two types of spherically-shaped buoys have become quite popular in oceanographic measurement systems. Both have a rigid shaft which extends radially downwards from the spherical float, forming a "ball-in-socket joint" where the spheres turn in the ocean support. One type, called *Waverider* (reference 35), incorporates vertical fins near the bottom end of its shaft so that it will tilt in response to the orbital currents of the passing waves (see figure 6.7 (a)). This behavior serves as a reminder of one of the locations not to place high-drag components for an MBCS buoy application.

The other type, called *Minimet* (TM) (reference 36) (figure 6.7 (b)), is referred to as a "stiff buoy" because it counters the tendency to tilt by means of a weight suspended from a line attached to the bottom end of its shaft. A buoy of this type will *heave* up and down and *surge* back and forth in response to the waves, will *yaw* in response to the slightest horizontal force couple, but in the meantime will maintain its antenna in a near-vertical position. See appendix D (parts D4.1 and D4.3) for analyses of the stabilities of two members of this class of buoy. Because of this inherent stability against tilt, the stiff version of the pendulous spherical buoy is judged to be ideal for many of the MBCS applications. Henceforth, this configuration will be referred to as simply a *pendulous spherical buoy.*

6.3.4 Boat/Pendulum Buoy

The "stiffness" advantage of the pendulous spherical buoy can be retained while combining the pendulum with a specially provisioned boat hull. This offers the additional advantages of reduced drag and improved access to the station components. This configuration will be preferred over the pendulous spherical buoy where the station must be towed to its location and where it must be anchored or linked to a drogue in currents above two knots. This buoy configuration is a logical step to a propeller-driven station which actively maintains its assigned position. (See sections 6.4.4 for further discussion.)

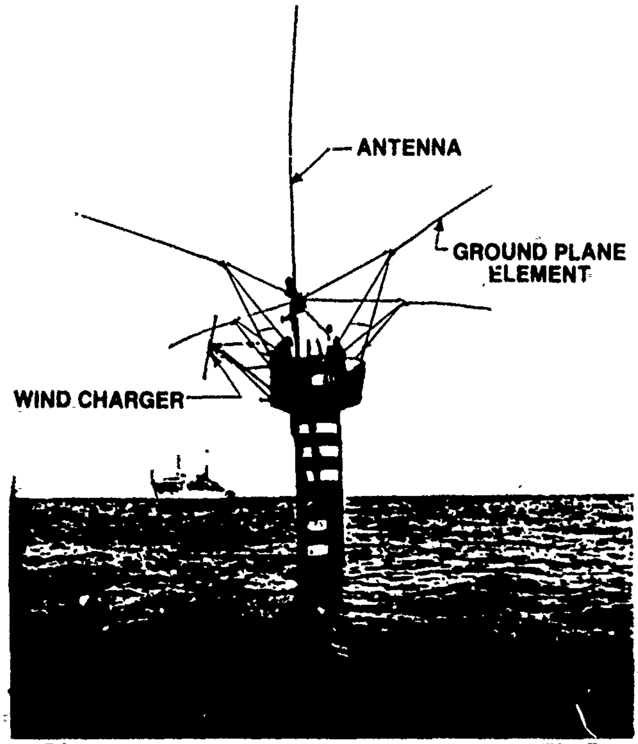


Figure 6.5. ISAR buoy.

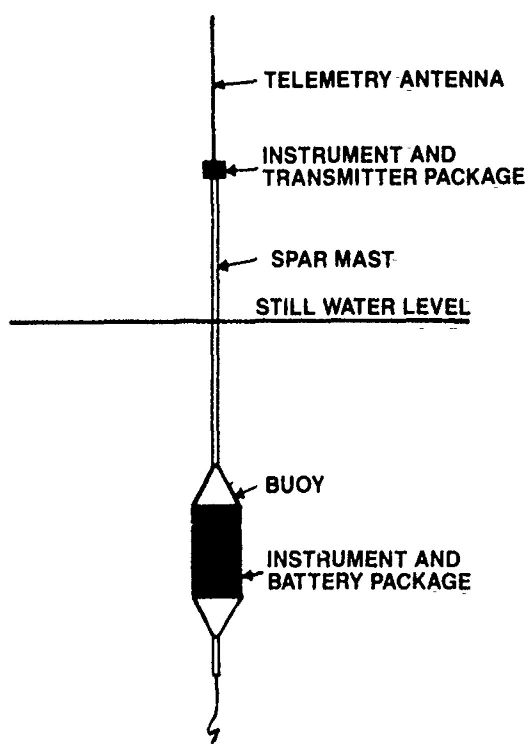


Figure 6.6. Submerged buoy with spar mast.

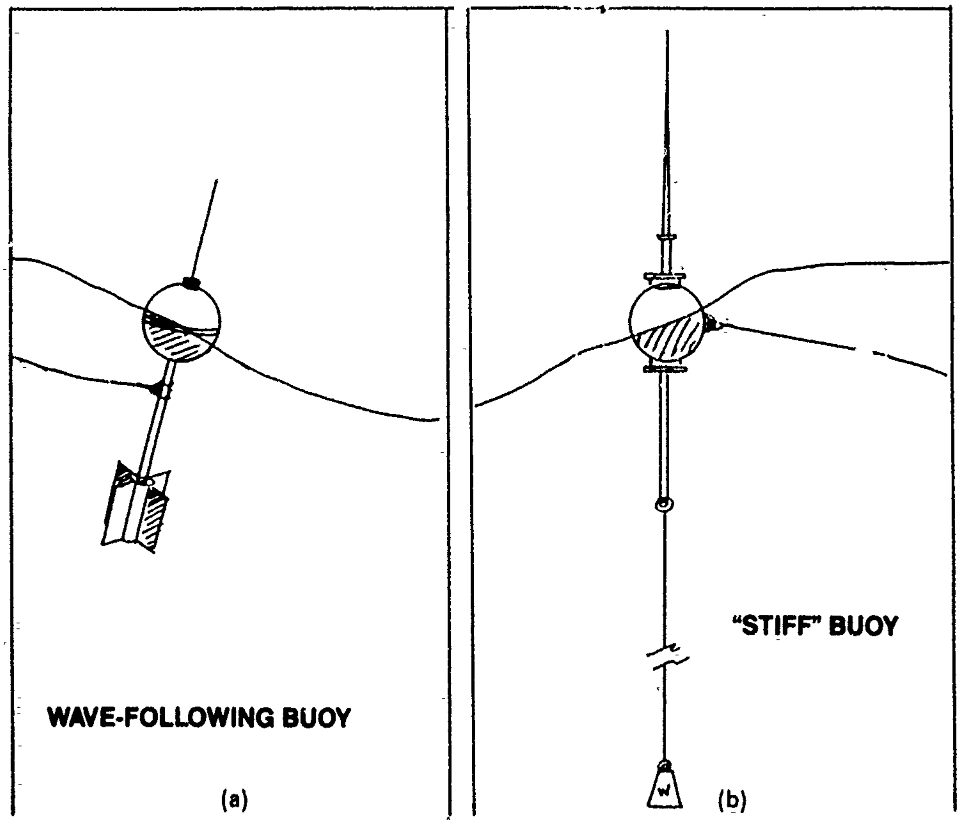


Figure 6.7. Pendulous buoys.

In the boat/pendulum buoy the shaft with its suspended weight pivots on an athwartship (transverse) axle. The shaft may either extend through an opening in the hull or may take the form a pivoting framework which reaches around the hull (see figures 6.8 and 6.11). This will allow the hull to pitch freely while imparting little more than heaving and surging motions through this axle to the pendulum and the antenna assembly extending above. Any tendency for the nearly cylindrical hull to roll will be countered by the righting moment of the lever arm and its suspended weight in the same manner that they function (in one plane) to right the spherical buoy. Except for the special pivoting provisions, the actual boat hull design tends to follow the seaworthy features of the Plank-On-Edge Buoy (TM) (reference 37) which has proven its sea worthiness since its conception and development starting in 1961.

Additional advantages of this hybrid buoy configuration are that its shape will reduce the deployment and equipment access problems for the larger MBCS stations. A ship may either tow or launch the station from davits in a manner similar to launching a life boat. The shape is also more amenable to air dropping a large station from the restricted rear cargo door of an aircraft. Access to the equipment will be greatly improved with the boat hull configuration, because the components may be reached through several hatches along the deck instead of through a single hatch, encumbered by an antenna mast.

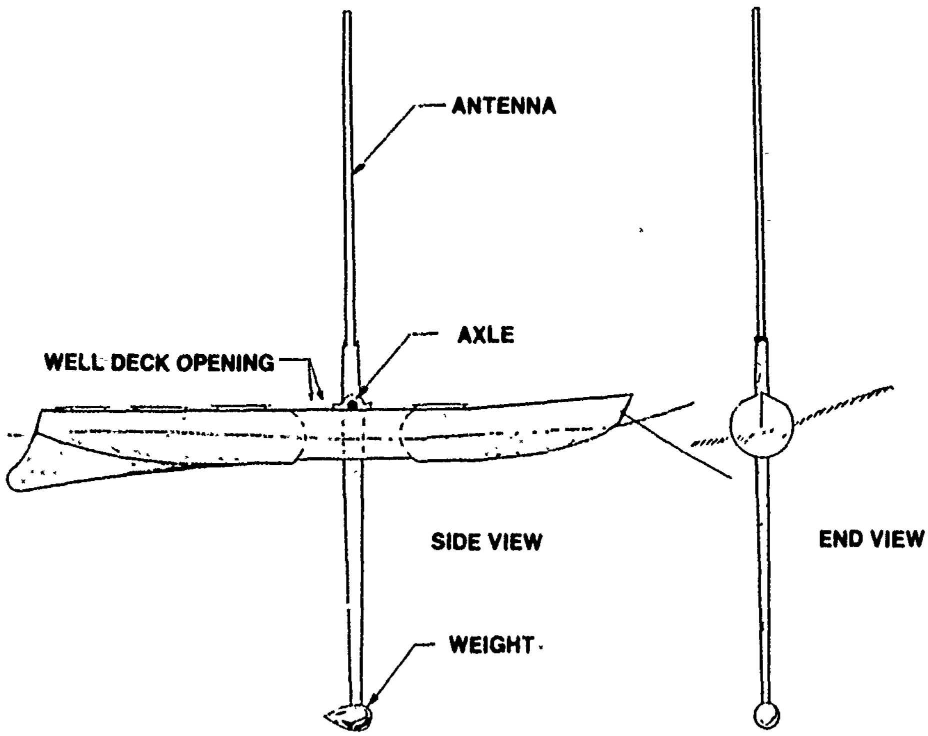


Figure 6.8. Boat/pendulum buoy.

For reasons of its low drag characteristic, the vertical "stiffness" it imparts to its antenna, the relative ease in handling of large-scale versions and its greater access to interior parts, this host/pendulum buoy should be considered for the MBCS applications requiring high energy power supplies. Unlike the spherical pendulous buoy, this boat/pendulum buoy has not been demonstrated. Performance studies of a quarter-scale model at sea and possibly in a wave tank are therefore recommended in order to verify the desirable performance characteristics which intuitively seem a certainty.

6.4 STATION KEEPING METHODS

6.4.1 Drifting Station

In many cases it may be cost effective to simply air drop a "remote" relay station on the up-current side of the desired operating area and later to drop a new station when the older one has drifted out of range or has failed. It can be seen by again referring to figure 6.1 that many of the surface currents can soon carry a buoy through the desired operating area in a short period of time, particularly if this area is made small by the long intervals (say 1000 nmi) separating this relay station from the pair of stations which it serves. Nevertheless, the added cost of a sequence of stations for one area would be partially offset by avoiding the great expense of automatic anchoring equipment, the added costs of some high-reliability features and a long-term energy supply. Being always prepared to air drop a new station would shorten the down-time following destruction by the enemy or an outright failure. Furthermore, the need for such a station may not continue beyond the life of the first one.

6.4.2 Drogue-Moored Station

The subsurface currents which have been measured are generally of less magnitude and are more consistent than the wind-driven surface currents. For these reasons an otherwise freely drifting station will probably stay longer in the desired area by tethering it to a drogue which is set to the depth of the more favorable currents. Unfortunately, there is not enough historical oceanographic data upon which to predict the subsurface currents for much of the world.

Some experience limited to the ocean within 60 nmi of San Diego has repeatedly demonstrated favorable results for this type of mooring. For example, the drift of sonobuoys has generally been dominated by surface currents. In order to reduce the flow noise at the hydrophones of experimental sonobuoys, a drogue is typically added at 300-foot depth and the surface float is streamlined. The effect, which was startling at first, is that the experimental sonobuoys appear to "swim" through the field of unmodified sonobuoys. Careful checks revealed that the sets (drift) of the buoys with drogues at 300 feet are very low and that the remainder of the field is pulled along by the surface current, typically at 1/2 knot.

Some of the advantages over anchoring to the sea floor are that the drogue and suppressor weight are relatively light, there is usually no chance of failure from sea floor chafing, and there is probably less need to outfit the system for a particular range of ocean depths.

6.4.3 Anchored Station

Perhaps the only passive way to keep a buoy from drifting from its assigned area is to permanently anchor it. The two buoy types which have been selected for this work do not lend themselves to supporting the large loads of the anchoring tackle plus the variable down-forces induced by the currents on the sometimes extremely long anchor line. These buoys require the help of auxiliary flotation which will support the mooring loads and redirect the final tension in a near-horizontal direction to the buoy which supports the MBCS equipment. This kind of mooring is shown in figure 6.9. A clump weight (shown) or a heavy chain holds the lower end to the sea floor. A hook anchor keeps the clump from sliding along the bottom. A deep float holds the chain upwards, far enough for the vulnerable support line to clear possible outcroppings of rocks. From there the line routes upwards, often along supporting floats, to near the surface. In deep water it is very important to make this line adequately strong while thin enough to keep the accumulative drag below an acceptable limit. Piano wire has been successfully used but a kink is disasterous because it induces a breaking point. Polypropylene offers the advantage of being slightly positive in buoyancy. Kevlar is very strong for a given cross section but it is expensive and sometimes requires additional buoyant supports.

From a navigational standpoint it is highly desirable to hold all the subsurface buoys and lines below the screws of passing ships. But such a mooring design would have to be tailored to the particular depth of ocean, with a comprehensive knowledge of the currents. Since this is not practical in many MBCS applications, the fairly safe alternative is to have a well-marked uppermost float riding on the ocean surface as it supports the wide range of down forces. The line linking this surface float and the MBCS buoy will route along the surface to lessen the chance of tangling with the rigging in the unlikely event of slack water.

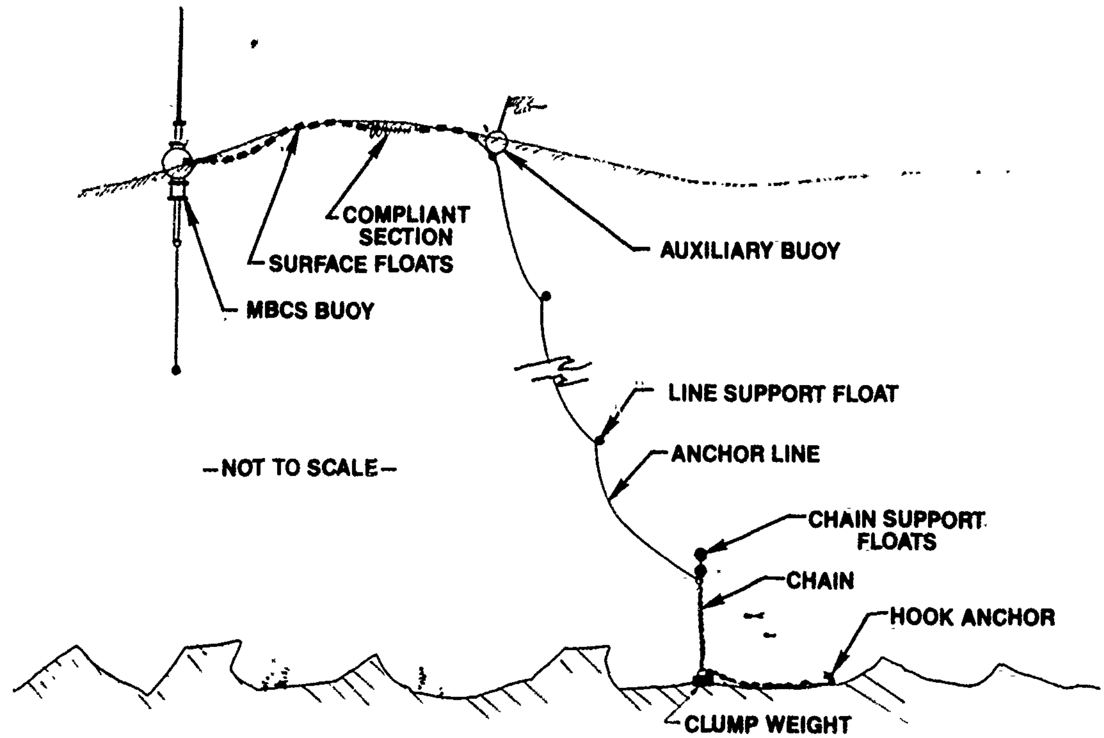


Figure 6.9. Anchored MBCS buoy.

After careful planning, the above type of anchoring can be accomplished in deep water from a surface ship. Accomplishing the same from an aircraft will call for additional ingenuity and probably some reduction in the success rate. The sequence of anchoring events may possibly proceed as follows:

1. The system is deployed from the rear cargo door of a low-flying aircraft. The packaged surface equipment, including half the coiled mooring line, is parachuted to the surface, followed in 3- to 5-seconds by the free-falling anchor package with the remainder of the mooring line.

2. The anchor package splashed into the surface and falls towards the ocean floor while pay'ng out mooring line, the antichafing chain and its support float. The hook anchor detaches from the clump so as to arrest the later tendency to be pulled along the sea floor.

3. Meanwhile, the surface package lands and its parachute and shroud lines are either dissolved or are safely jettisoned.

4. The coiled mooring line, subsurface floats and surface float pay out as they are pulled free by the falling anchor package and, later, by the set of the current.

5. The station extends its pendulum, erects its antenna and turns on.

6.4.4 Active Station Keeping

Active station keeping may be accomplished by a boat/pendulum buoy that has a substantial portion of its energy devoted to a propulsion mechanism, perhaps in the form of fuel oil for a small engine and propeller. The buoy's drift is slightly retarded and its bow is held into the sea by means of a small weighted drogue and 300 feet of line which is automatically deployed and recovered through a bull nose. By various means the operators on shore ascertain the set of this station and, during good weather, command it to travel on a selected magnetic heading at about 3 knots for a calculated period of time, with the antenna still erected but necessarily tilted a little forward. The station first recovers its drogue, follows these maneuvering instructions and then redeploys the drogue.

6.5 PREFERRED DESIGN SPECIFICATIONS

Three representative designs are described below to indicate the range of size and complexity of MBCS stations. Additional details are given in appendix D, where the stability against tilt for each of these stations is computed for an idealized sea state 6. (An idealized sea state 6 is one in which the waves are generated from one source and are therefore free from interference effects which are hard to predict and treat mathematically). These results are briefly summarized at the end of each subsection they apply to.

6.5.1 Combination Master/Slave Station for Initial Evaluation

This station is the ship-launched pendulous buoy which is planned to be used for evaluation purposes in initial operational phase of the MBCS Program. Coincidentally, this station also fits the category of a preferred design for a ship deployment. It has the desired shape of the pendulous spherical buoy selected in section 6.3.3 and it can support an energy supply sufficient for about 100 hours of operation on a master station radiating 300 watts RF power. This station will be tethered to an auxiliary surface float which will be anchored to the sea floor in a manner quite similar to that which is described in section 6.4.3 and diagrammed in figure 6.9.

This buoy (shown in figure 6.10) consists of a 58-inch diameter steel sphere having a downward-extending battery compartment and rigid 8-foot shaft which connects to a 40-foot support line and a 700-pound ballast weight. On top of the sphere is an access hatch and an integral short mast supporting navigational devices, a telemetry antenna, and a J-antenna which extends to 21 feet above the average ocean surface. Next to the hatch are the air induction and exhaust fitting for the battery.

A 42-kWh zinc-air battery occupies the lower compartment and extends into the bottom of the sphere where its output is converted to maintain a charge on a 28-volt nickel-cadmium battery. The radio and other electronic equipment are contained in the sphere.

The mooring line fixture extends horizontally from the right of the sphere in figure 6.10. This serves as a lever arm so that even a slight tension in the horizontally mounted mooring line will keep the buoy from rotating and winding up the line. Since the mooring equipment will be tailored to an anchorage location which has not yet been selected and since such information would not be useful for the stability study, no details are given. Additional information, however, is made available regarding the parameters of this buoyed station in the course of the stability analysis in appendix D (part D4.1).

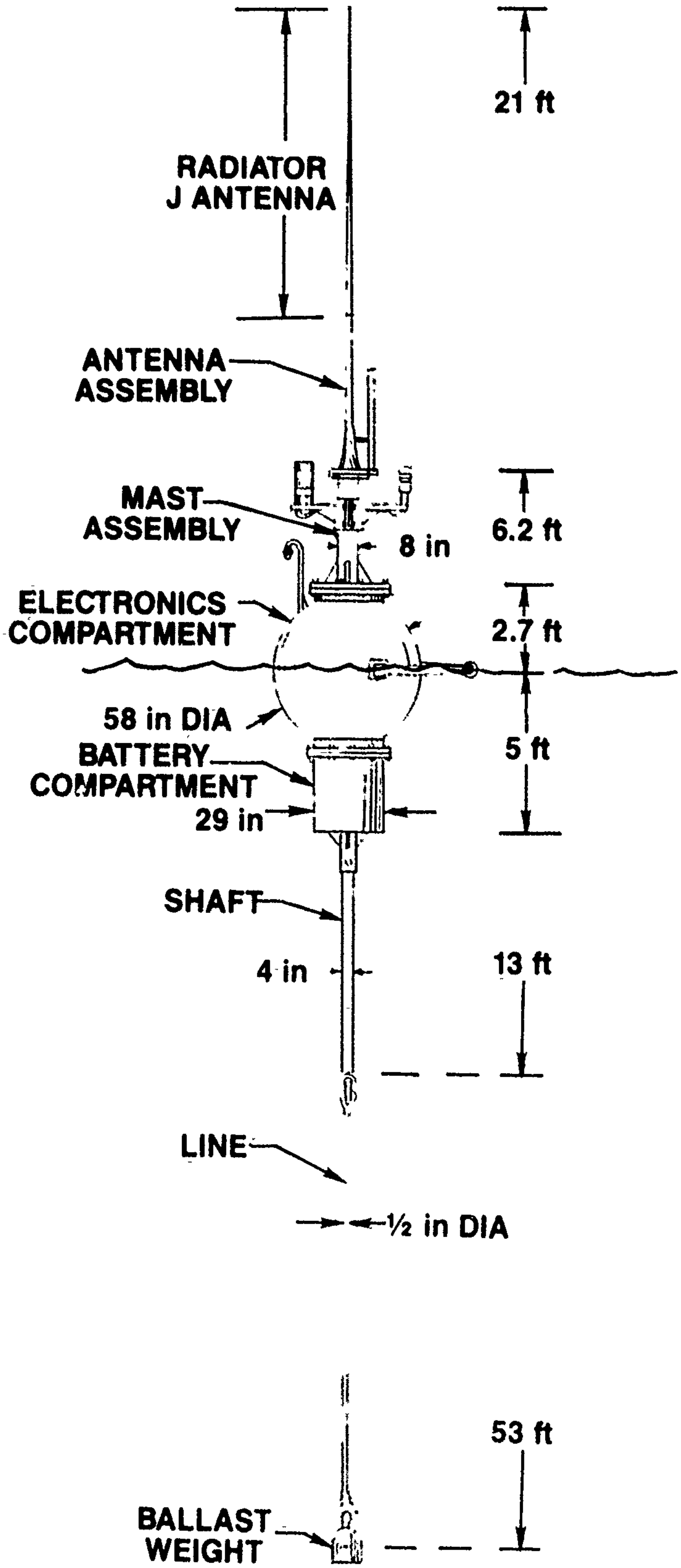


Figure 6.10. Combination master/slave station.

The maximum expected tilt of this station's antenna was computed in appendix D (part D4.1) for an idealized sea state 6 to be 8.8 degrees from the vertical.

6.5.2 Master Station with a Horizontally-Polarized Antenna

This station is a large MBCS Master Station of the boat/pendulum type. It may either be carried aboard a specially equipped ship or be towed to the assigned area by a more general purpose vessel. Due to the large investment associated with it, this type of station is likely to be anchored to the sea floor. If not, it should at least be moored to a drogue to suppress the tendencies to yaw. The station's large size is necessitated by the heavy and bulky zinc-air battery (5000 pounds and 33 cubic feet) needed for frequent transmissions (50-percent duty cycle) throughout a 90-day period. A horizontally-polarized antenna is required for compatibility with other stations within the network. (However, this same station could just as well be outfitted with a vertically-polarized antenna, or both).

Figure 6.11 shows this station with its pendulous boat-hull configuration. The hull is 30-feet long with a 4-foot beam. Except where it narrows and turns up at the ends, the hull is a uniform cylinder which is flattened on the top surface for hatches and a walkway. The penduluous frame extends just outboard of both sides of the hull where it pivots on an axle located amidships. The frame closes together, well above and below the hull, so that the entire assembly can be pivoted to a nearly horizontal attitude for storing, towing, and transporting. On station, the antenna structure is attached to this assembly before the ballast weight is allowed to swing down to pull the entire pendulous assembly to its vertical position.

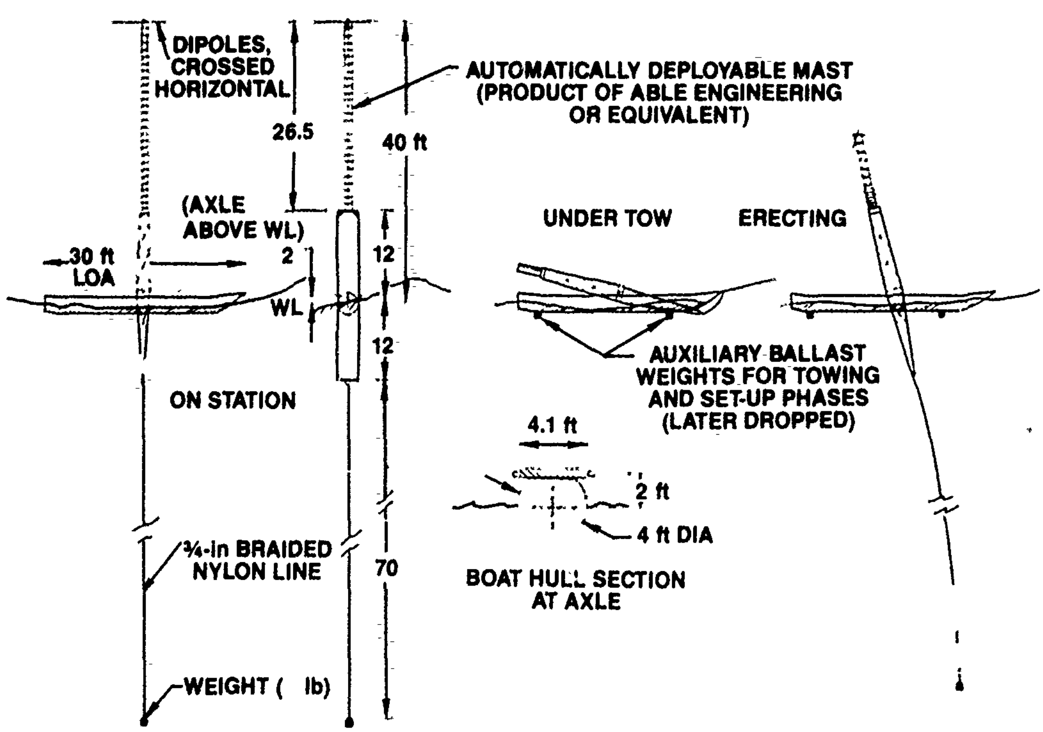


Figure 6.11. Master station with horizontally-polarized antenna.

The active part of the antenna consists of horizontally-crossed dipoles, 40 feet above the average ocean surface. A 700-kWh zinc-air battery is positioned under several access hatches along the flat surface of the hull. Air induction and exhaust hardware extend upward through the deck and through flexible tubes leading part way up the antenna support structure.

Additional details regarding the weights, displacements and drags of this station are given in appendix D (part D4.2) where the maximum tilt for an idealized sea state 6 was found to be 2.9 degrees in the transverse vertical plane.

6.5.3 Covert Station Which Rarely Transmits

This air-deployable station consists of a 4-foot long by 8-inch diameter aluminum cylinder, tightly wrapped in a neoprene bag which will inflate to a 2-foot diameter and encompass half of the cylindrical surface at splashdown. Shortly afterwards, the ballast weight reaches the end of its bridle and line, triggering the J-antenna to erect from the upper end of the cylinder.

Figure 6.12 shows this station before and after deployment. The cylinder extends 20 inches below the inflated sphere where four 11-inch arms are hinged outward to support the upper ends of the bridle leading to a 23-foot line and 50-pound net ballast weight. The bridle serves the same function as the rigid shaft of the previously-described pendulous buoys. As long as there is tension in each of the four bridle cords, the combination of members closely resemble a rigid body serving as a lever arm extension of the buoy assembly. The advantage of this configuration is that the cords permit the assembly of a more compact air-drop package. The cylinder extends 6 inches above the sphere where it joins the erected antenna. The top of the antenna is 16 feet above the average ocean surface.

In the bottom of the cylinder resides a 35-pound nickel-cadmium battery which has been selected for its exceptionally high discharge rate. This battery is capable of supplying the rare peak power demands of 620 W for the transmitter and the continuous 0.7 W requirement of the receiver until its 90 Wh of energy is consumed. At an average of 1 Wh, the life of the station would be less than four days. The energy could be increased to 6000 Wh by substituting a 50-pound lithium battery for the dead weight of the suspended ballast. (By having the lithium battery in a separate, detachable package, special safety precautions need not involve the entire station, and the option could wait the final decision of whether to launch a long or short-lived station.) The current from the lithium battery would be conducted through the support lines to a circuit which charges the nickel-cadmium battery. It follows that the active life of this small station with this battery combination would exceed eight months at an average of 1 W or one month at 8 W.

The maximum tilt of this station was computed in appendix D (part D4.3) to be 25.2 degrees in an idealized sea state 6.

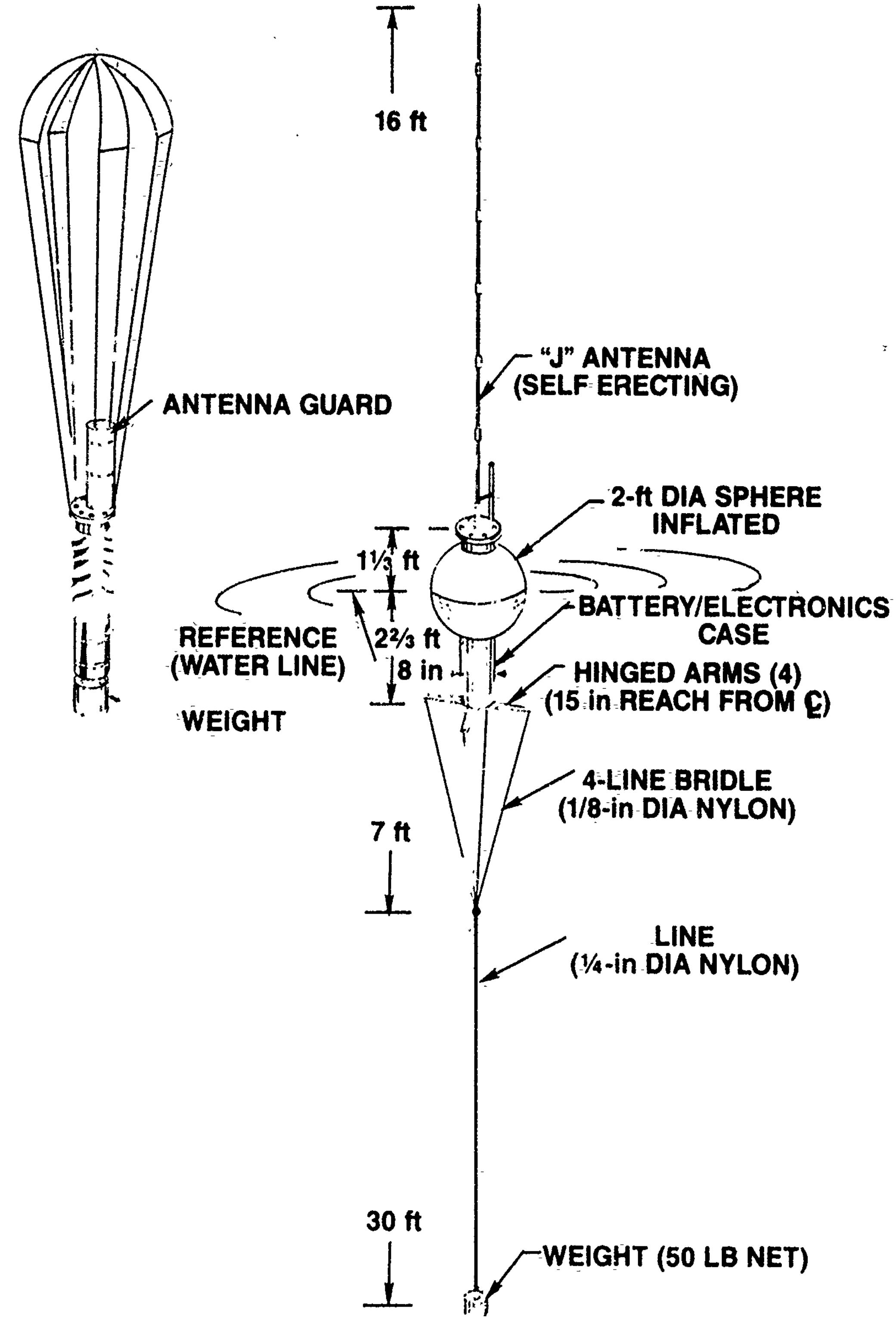


Figure 6.12. Air-deployed covert station which rarely transmits.

7.0 MBCS BUOY STATION SURVIVABILITY

7.1 ENVIRONMENTAL FACTORS

Techniques have been steadily improved for increasing the longevities of ocean buoys and their mooring and anchoring schemes. They have reached a point that an experienced or well-schooled buoy system designer can deploy a nonradical product with a fair probability of it surviving the ocean and atmospheric forces and perhaps remain anchored for a year or longer. All this depends on a number of factors such as the severity of storms, the depth of the water, and the complexity of the components imposed by the mission. By a broader definition, a station's survival also depends on whether it continues to function; i.e., whether its energy system, sensors, signal processing, and radio equipment (including the antenna and other components) continue to work in harmony. Clearly, a tutorial discussion on all the considerations is beyond the scope of this report.

7.2 HUMAN/HARDWARE FACTORS

7.2.1 Peacetime Survivability

Buoy systems which are much larger than a bottle with a note in it are generally made apparent to passing ships by radar reflectors, flashing lights, and color coding in accordance with the International Rules, Coast Guard, or the cognizant organization for the particular body of water. The effect on most ships is to cause them to steer well clear. The natural curiosity of some seafarers will cause them to veer off course for a close-up inspection and an occasional boarding. Whether the system survives the close approach depends on the vulnerability of the peripheral equipment, e.g., unmarked mooring lines which stretch along the surface. Whether it survives the boarding depends entirely on the nature of the intruder. The situation may have been recorded somewhere, but the story has slowly leaked through the oceanographic community that it has been a common occurrence for anchored U.S. Government buoy systems in the Atlantic to be periodically inspected by unknown parties which cause no damage but carefully close the hatches as they depart. Inspections are said to be much more frequent on new types of buoy systems.

The question will not be answered here on how to discourage boarders. A sign saying, "STAY OFF, PROPERTY OF THE U.S. NAVY" is apt to invite treasure seekers on board, who are not particularly empathetic of the Navy and have no fear of it when there are no ships or planes in sight. The ISAR buoy (figure 6.5) survived two years at sea and was returned to port after being anchored 200 nmi southwest of San Diego. The buoy's sign admitted U.S. Navy custodianship and gave the phone number to call for further information. The only boarders in all that time were the engineers who made their bimonthly inspections, and one dead bird.

7.2.2 Wartime Survivability

If our enemy realizes that we benefit from buoyed MBCS relay stations he will probably try to jam (see section 1.3) or destroy them. In order to destroy the stations the enemy must know where they are. If the U.S. Government has had its well-marked and well-lighted MBCS buoys at their assigned locations long before the hostilities commence, simply turning off the lights and removing the radar reflectors would not suddenly make the unofficial boarders and inspectors forget the buoy locations. The pros and cons of several other methods of prolonging the life of wartime MBCS relay stations are discussed below.

Last minute deployment. The stations could be held in reserve until a war was imminent. They would then be rapidly deployed by well-rehearsed methods. These stations would be camouflaged and made as radar transparent as possible. One problem is that a radio black-out might continue for a considerable duration before the more permanent stations could be deployed by forces which where otherwise occupied by major problems.

Pop-up Stations. These pressure-tight stations could be held 200 feet below the ocean surface until they were separately signaled to surface in the operating mode. Each signal could be accomplished by air-dropping a package (or launching it from a submarine) which acoustically transmits a coded signal of sufficient strength to trigger the station's release mechanism from a range up to 5 nmi. Each station is anchored above a seamount in otherwise fairly shallow water (4000 feet or less). A 3-point mooring is used for stabilizing the depth of the submerged station as currents change in magnitude. In the course of positioning the station, a single 400-foot line runs almost vertically from the apex of the three anchor lines to the buoy while it is yet on the surface.

The operability of the station is tested before it is commanded to draw itself down to a hydrostatic depth of 200 feet. For this purpose a 1-HP submersible oceanographic motor runs for about 30 minutes while draining 1000 W or a total of 500 Wh from a battery. The submerged buoyancy of each station is 5000 pounds. (Alternately, but not favored, the deploying ship pulls on a line or supplies the power through an electrical cable to draw the buoy to depth). When the buoy is at its (standby) submerged position, its listening system is tested by transmitting acoustic codes from the ship (but not the one which will effect release). The station acoustically acknowledges the receipt of one code and responds to another code with "housekeeping" information. This information includes the conditions of the energy source(s), how much water if any has entered the buoy, the leakage resistance of the antenna to the ocean, and other items of prime interest. At later times the condition of each station can be rechecked by an aircraft (or ship or submarine) which drops a sonobuoy for listening to the station response, and an acoustic package which emits the correct set of codes.

Problems with the pop-up station concept: A station at a reasonable hydrostatic depth is a menace to submarines. Passing the housekeeping tests does not ensure that a particular station will function properly when it surfaces. These stations will be fairly expensive and require engineering talent that is hard to guarantee through competitive bids. Enemy countermeasures to these stations are security leaks as to their locations, while every friendly submarine must be told where (not what) they are.

Piggy-back Stations. Expand the weather surveillance program and anchor a few more Monster buoys at strategic MBCS locations. In a surreptitious manner add a MBCS capability to these large weather buoys, but use it only briefly in peacetime to verify its efficacy.

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APPENDIX A

Listing of power sources considered as candidates for the various requirements.

Tables are included for the following requirements:

Table No.	Average Power Required (Watts)	Endurance (Months)
A.1	1	1
A.2	1	6
A.3	10	1
A.4	10	3
A.5	100	1
A.6	100	3
A.7	1000	1
A.8	1000	3

Table A.1. Power level, 1.0 watt; time, 1 month.

POWER SOURCE (IDENT NO.)	COST ($)	WEIGHT (POUNDS) (IN AIR)	VOLUME (CU IN)	CRITICAL MATERIALS ETC.
ZINC-AIR DEPOLARIZED CELL (1.1.11)	18	10	240	REQUIRES NICAD STORAGE BATTERY AND AIR
PB-ACID AUTO TYPE CELL (1.2.1)	40	36	585	TEMP DEPENDENT DEGRAD'TN
ALKALINE ZINC CELL (1.1.2)	57	21	240	
LECLANCHE TYPE CELL (1.1.1)	58	23	347	
LITHIUM-INORGANIC CELL (1.1.3)	61	3	62	
MG-MNO2 PRIM DRY CELL (1.1.2)	85	13	253	
PB-ACID STATIONARY (1.2.2)	104	82	1114	TEMP DEPENDENT DEGRAD'TN
ALKALINE MERCURIC-OXIDE (1.1.8)	143	18	156	MERCURY IS USED
LITHIUM ORGANIC (1.1.4)	314	8	141	
SOLAR CELL (4.1.1)	340	23	540	1 WK PB-ACID BATT INCL
SILVER-ZINC PRIM CELL (1.2.4)	458	10	144	USES SILVER
SILVER-ZINC SECOND CELL (1.2.4)	567	13	223	USES SILVER/PRESS-EQUAL
SEALED NICKEL-CADMIUM (1.2.3)	832	86	1282	USES NICKEL
TEN WATT GF TG (2.1.1)	893	42	3798	PROPANE FUELED
100 WATT WIND GEN 10 MPH (4.2.1)	2040	138	202	REQUIRES ANNUAL MAINT.
1 WATT RIG (3.1.1)	9165	4	21	PU 238 PROVIDED BY ERDA
1 WATT RIG (3.1.1)	19024	750	2771	STRONTIUM 90 ISOTOPE

Table A.2. Power level, 1.0 watt; time, 6 months.

POWER SOURCE (IDENT NO.)	COST ($)	WEIGHT (POUNDS) (IN AIR)	VOLUME (CU IN)	CRITICAL MATERIALS ETC.
ZINC-AIR DEPOLARIZED CELL (1.1.11)	70	57	1414	REQUIRES AIR
ALKALINE ZINC CELL (1.1.2)	220	126	1510	
LECLANCHE TYPE CELL (1.1.1)	224	141	2094	
LITHIUM-INORGANIC CELL (1.1.3)	245	19	373	
SOLAR CELL (4.1.1)	340	23	540	1 WK PB-ACID BATT INCL
MG-MNO2 PRIM DRY CELL (1.1.2)	387	80	1528	
PB-ACID STATIONARY (1.2.2)	506	493	6732	TEMP DEPENDENT DEGRAD'TN
TEN WATT GFTG (2.1.1)	907	90	5051	PROPANE FUELED
100 WATT WIND GEN 10 MPH (4.2.1)	2040	138	202	REQUIRES ANNUAL MAINT AND STORAGE BATTERY
SILVER-ZINC PRIM CELL (1.2.4)	2645	60	869	USES SILVER
SILVER-ZINC SECOND CELL (1.2.4)	3302	80	1346	USES SILVER/PRESS-EQUAL
SEALED NICKEL-CADMIUM (1.2.3)	4904	520	7746	USES NICKEL
1 WATT RIG (3.1.1)	9165	4	21	PU 238 PROVIDED BY ERDA
1 WATT RIG (3.1.1)	19024	750	2771	STRONTIUM 90 ISOTOPE

Table A.3. Power level, 10 watts; time, 1 month.

POWER SOURCE (IDENT NO.)	COST ($)	WEIGHT (POUNDS) (IN AIR)	VOLUME (CU IN)	CRITICAL MATERIALS ETC.
ZINC-AIR DEPOLARIZED CELL (1.1.11)	90	98	2340	REQUIRES AIR AND NICAD STORAGE BATTERY
PB-ACID AUTO TYPE CELL (1.2.1)	177	363	5850	TEMP DEPENDENT DEGRAD'TN
ALKALINE ZINC CELL (1.1.2)	340	209	2520	
LECLANCHE TYPE CELL (1.1.1)	355	233	3467	
LITHIUM-INORGANIC CELL (1.1.3)	390	32	618	
MG-MNO2 PRIM DRY CELL (1.1.2)	625	132	2530	
PB-ACID STATIONARY (1.2.2)	821	816	11143	TEMP DEPENDENT DEGRAD'TN
TEN WATT GFTG (2.1.1)	965	127	6034	PROPANE FUELED
100 WATT WIND GEN 10 MPH (4.2.1)	2176	296	2018	REQUIRES ANNUAL MAINT.
SOLAR CELL (4.1.1)	3176	226	5396	1 WK PB-ACID BATT INCL
SILVER-ZINC PRIM CELL (1.2.4)	4362	99	1438	USES SILVER
SILVER-ZINC SECOND CELL (1.2.4)	5449	132	2229	USES SILVER/PRESS-EQUAL
TEN WATT RIG (3.1.1)	47924	3150	13575	STRONTIUM 90 ISOTOPE
25 WATT RIG (3.1.1)	70524	4200	22167	STRONTIUM 90 ISOTOPE
25 WATT RIG (3.1.1)	87024	1900	19500	SR 90 LIGHTWEIGHT UNIT

Table A.4. Power level, 10 watts; time, 3 months.

POWER SOURCE (IDENT NO.)	COST ($)	WEIGHT (POUNDS) (IN AIR)	VOLUME (CU IN)	CRITICAL MATERIALS ETC.
ZINC-AIR DEPOLARIZED CELL (1.1.11)	249	285	7020	REQUIRES AIR AND NICAD STORAGE BATTERY
ALKALINE ZINC CELL (1.1.2)	1020	630	7560	
LITHIUM-INORGANIC CELL (1.1.3)	1122	95	1853	LARGE CELL TECHNOLOGY
TEN WATT GFTG (2.1.1)	1123*	314	11002**	PROPANE FUELED
100 WATT WIND GEN 10 MPH (4.2.1)	2176	296	2016	REQUIRES ANNUAL MAINTENANCE
PB-ACID STATIONARY (1.2.2)	2414	2449	33429	TEMP DEPENDENT DEGRAD'TN
SOLAR CELL (4.1.1)	3176	226	5329	1 WK PB-ACID BATT INCL
SILVER-ZINC PRIM CELL (1.2.4)	13038	297	4313	USES SILVER
SILVER-ZINC SECOND CELL (1.2.4)	16297	396	6686	USES SILVER/PRESS-EQUAL
TEN WATT RIG (3.1.1)	47924	3150	13575	STRONTIUM 90 ISOTOPE
25 WATT RIG (3.1.1)	70524	4200	22187	STRONTIUM 90 ISOTOPE
25 WATT RIG (3.1.1)	87024	1900	19500	SR 90 LIGHTWEIGHT UNIT

*INCLUDES WEIGHT OF FUEL

**INCLUDES VOLUME OF FUEL

Table A.5. Power level, 100 watts; timc, 1 month.

POWER SOURCE (IDENT NO.)	COST ($)	WEIGHT (POUNDS) (IN AIR)	VOLUME (CU IN)	CRITICAL MATERIALS ETC.
1250W LPG ENG/GEN (2.2.1)	1234	967*	31400**	SEMI-ANNUAL MAINT REQ'D
ZINC-AIR DEPOLARIZED CELL (1.1.11)	1410	1120	21300	REQUIRES AIR AND NICAD STORAGE BATTERY
PB-ACID AUTO TYPE CELL (1.2.1)	1549	3633	58500	TEMP DEPENDENT DEGRAD'TN
100 WATT WIND GEN 10 MPH (4.2.1)	3537	1884	20160	REQUIRES ANNUAL MAINT.
LITHIUM-INORGANIC CELL (1.1.3)	3682	317	6178	LARGE CELL TECHNOLOGY
100 WATT GFTG (2.1.1)	4025	1125*	44815**	PROPANE FUELED
ALKALINE ZINC CELL (1.1.2)	4720	2140	34560	
PB-ACID STATIONARY (1.2.2)	7989	8165	111431	TEMP DEPEDENT DEGRAD'TN
SOLAR CELL (4.1.1)	31536	2261	53960	1 WK PB-ACID BATT INCL
100 WATT RIG (3.1.1)	180025	2700	28325	STRONTIUM 90 ISOTOPE

*INCLUDES WEIGHT OF FUEL

**INCLUDES VOLUME OF FUEL

Table A.6. Power level, 100 watts; time, 3 months.

POWER SOURCE (IDENT NO.)	COST ($)	WEIGHT (POUNDS) (IN AIR)	VOLUME (CU IN)	CRITICAL MATERIALS ETC.
1250W LBG ENG/GEN (2.2.1)	1522	2551*	81800**	SEMI-ANNUAL MAINT REQ'D
AIR DEPOLARIZED CELL (1.1.10)	2271	2851	70200	REQUIRES AIR
100 WATT WIND GEN 10 MPH (4.2.1)	3537	1884	20160	REQUIRES ANNUAL MAINT.
ZINC-AIR DEPOLARIZED CELL (1.1.11)	3980	2740	63936	REQUIRES AIR AND NICAD STORAGE BATTERY
100 WATT GFTG (2.1.1)	4096	2997*	94495**	PROPANE FUELED
ALKALINE ZINC CELL (1.1.2)	14010	6200	100224	
PB-ACID STATIONARY (1.2.2)	23918	24494	334292	TEMP DEPEDENT DEGRAD'TN
SOLAR CELL (4.1.1)	31536	2261	53960	1 WK PB-ACID BATT INCL
100 WATT RIG (3.1.1)	180025	2700	28325	STRONTIUM 90 ISOTOPE

*INCLUDES WEIGHT OF FUEL

**INCLUDES VOLUME OF FUEL

Table A.7. Power level, 100 watts; time, 1 month.

POWER SOURCE (IDENT NO.)	COST ($)	WEIGHT (POUNDS) (IN AIR)	VOLUME (CU IN)	CRITICAL MATERIALS ETC.
3.5KW DIESEL ENG/GEN (2.2.1)	2304	14915*	60360**	SEMI-ANNUAL MAINT REQ'D
125CW LPG ENG/GEN (2.2.1)	2530	10975*	308600**	SEMI-ANNUAL MAINT REQ'D
ZINC-AIR DEPOLARIZED CELL (1.1.11)	10500	9200	211200	REQUIRES AIR AND NICAD STORAGE BATTERY
1KW WIND GEN 10 MPH AVG (4.2.1)	18025	12000	200000	REQUIRES ANNUAL MAINT.
ALKALINE ZINC CELL (1.1.2)	44500	20500	345000	
PB-ACID STATIONARY (1.2.2)	79669	81647	1114308	TEMP DEPENDENT DEGRAD'TN
SOLAR CELL (4.1.1)	315144	22610	539600	1 WK PB-ACID BATT INCL

*WEIGHT OF FUEL INCLUDED

**VOLUME OF FUEL INCLUDED

Table A.8. Power level, 1000 watts; time, 3 months.

POWER SOURCE (IDENT NO.)	COST ($)	WEIGHT (POUNDS) (IN AIR)	VOLUME (CU IN)	CRITICAL MATERIALS ETC.
3.5KW DIESEL ENG/GEN (2.2.1)	2462	43715*	133080**	SEMI-ANNUAL MAINT REQ'D
125DW LPG ENG/GEN (2.2.1)	5410	32575*	913400**	SEMI-ANNUAL MAINT REQ'D
1KW WIND GEN 10 MPH AVG (4.2.1)	18024	12000	200000	REQUIRES ANNUAL MAINT.
ZINC-AIR DEPOLARIZED CELL (1.1.1.1)	22488	28512	702000	REQUIRES AIR AND NICAD STORAGE BATTERY
ALKALINE ZINC CELL (1.1.2)	134500	62000	1034000	
PB-ACID STATIONARY (1.2.2)	238959	244942	3342924	TEMP DEPENDENT DEGRAD'TN
SOLAR CELL (4.1.1)	315145	22610	539600	1 WK PB-ACID BATT INCL

*WEIGHT OF FUEL INCLUDED

**VOLUME OF FUEL INCLUDED

APPENDIX B
SEAWATER BATTERY

INTRODUCTION

Figure B.1 shows in a simplified manner the major chemical reaction associated with the seawater battery. The primary anode reaction occurs with a magnesium atom reacting with the seawater electrolyte to produce a magnesium ion and two electrons. These electrons flow through an external resistive load and into the electro-chemically opposite cathode. The electrons then react with a water molecule at the cathode surface to produce hydrogen gas and hydroxide ions. Magnesium ions produced at the anode migrate toward the cathode and eventually unite with the hydroxide ions to form magnesium hydroxide. The sodium and chlorine ions in the sea water provide mobility to the electron and conduct the current flow through the electrolyte.

As the energy system functions, the magnesium anode is slowly consumed and quantities of seawater are decomposed; however, the cathode remains inert through the reaction. Consumption rate of the anode is about 0.008 to 0.012 inches per day, thus providing extremely long life capability.

Referring now to figure B.2, you can see where this energy system fits into the picture. The applicable power/life characteristics partially overlap areas previously occupied by radioisotopes, lead-acid batteries, solid electrolyte batteries, seawater-activated batteries and fuel cells. The versatility of the seawater battery is such that the high efficiency and low cost advantages are realizable throughout a vast power level range and in lifetime requirements from one month to as long as several years.

The seawater battery is a dry and inert unit until it is submerged in seawater, whereupon it comes up to full power within several seconds and continues to produce the electrical energy until the magnesium anode is consumed. The cells are free floating and can therefore, be deployed at any ocean depth without regard to pressure protection. This is not the case for most batteries, fuel cells, or radioisotope systems.

It is clear the seawater battery fulfills important existing needs and also extends the state-of-the-art to provide new capabilities heretofore not possible. This new technology provides the oceanographer the flexibility to design his system to upgrade power/life mission objectives and at a low cost in keeping with budget limitations.

The NOSC seawater battery has been specifically designed for submersible service in oceanographic applications where an economical lightweight source of electric power is required. Operation relies on the galvanic corrosion of dissimilar metals when submerged in seawater. The NOSC battery is available in single and multiple cell packages, depending on power requirement specifications. Some of the more important features of the seawater battery are:

Long operating life — The system is constructed of components chosen for their functional durability under normal and adverse environmental conditions. The exceptionally long operating life of the seawater battery results from its unique design characteristics and the inherent long duration energy processes involved.

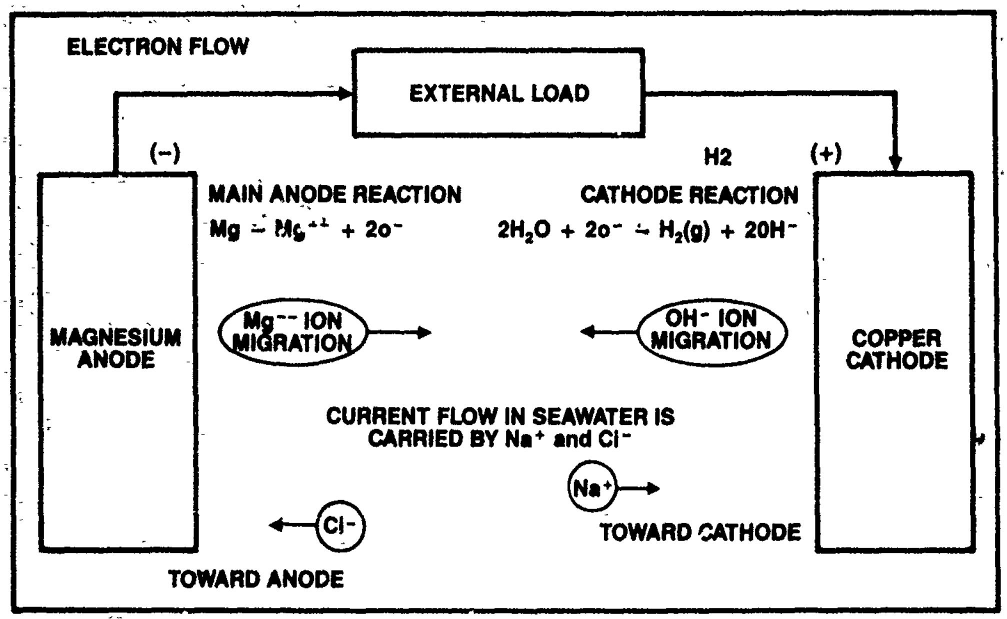

Figure B.1. Chemistry of the NOSC seawater battery.

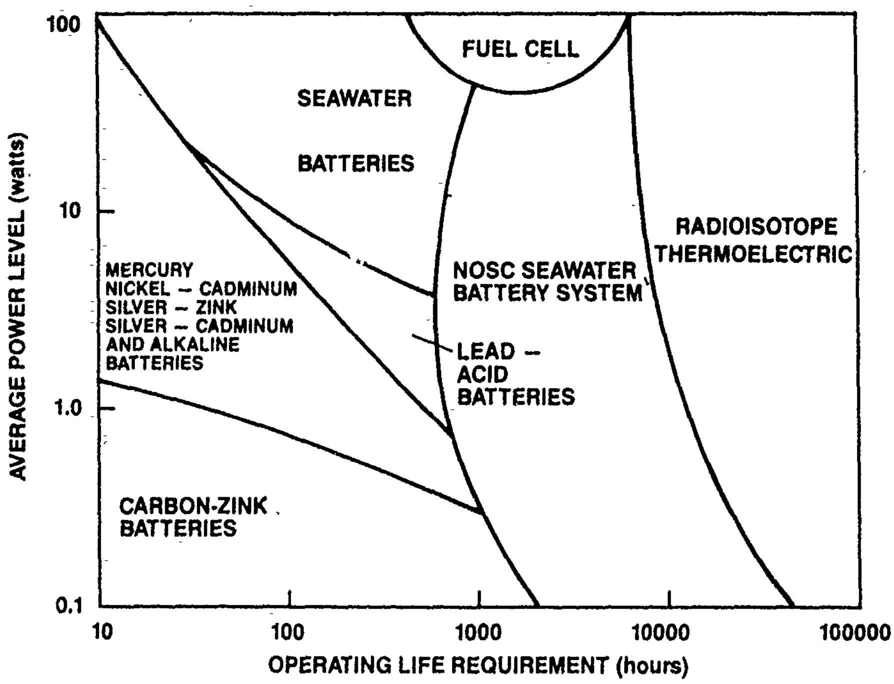

Figure B.2. Energy source applicability after full development of the NOSC seawater battery.

Economical — Aside from its original low cost, the systems environmental endurance and longevity features provide an economical operating life for producing electric power as compared to products of more conventional design. Energy densities exceeding 100 watt hours per pound at a cost of 10 cents K per watt hour can be realized with this battery.

Compact — They are extremely compact compared to more conventional designs with energy densities as high as 2.6 watt hours per cubic inch. This feature is important where NOSC energy systems are used as components in packaged system applications.

Unlimited Shelf Life — The seawater cell is dry and inert until submerged. Therefore, storage time is essentially limitless. Transportation and handling of hazardous electrolytes are eliminated. Shipboard and remote battery charging operations are never required.

Controlled Power — Each seawater battery has a solid-state controller which monitors voltage output levels and keeps them to within narrow limits of load requirements covering a wide range of power demands. Voltage excursions found in conventional battery systems are nonexistent for these batteries.

Deep Submergence Capability — Certain oceanographic applications require power sources which perform properly under deep submersible service conditions. They can be engineered for deep submersible service and long duration.

Mechanical Reactivations — Depleted NOSC seawater batteries are readily reactivated by replacing the required number of energy cells on location. The controller is reusable, and any residual cell components at the end of service life are simply discarded.

APPENDIX C

Descriptive data of some of the various power sources identified in appendix A and in the report proper.

Information on the following power sources are included

No.	Name
1.1.1	Leclanche (Carbon-Zinc) Dry Battery
1.1.2	Alkaline-Manganese Dioxide Battery
1.1.3	Lithium Inorganic Battery
1.1.4	Lithium Organic Cells
1.1.8	Mercuric Oxide Battery
1.1.11	Zinc-Air Cell
1.2.1	Lead-Acid, Automotive Battery
1.2.2	Lead-Acid, Stationary Battery
1.2.3	Sealed Nickel-Cadmium (NICAD) Battery
1.2.4	Silver-Zinc Battery
2.1.1	Thermoelectric Generators, Gas-Fired (GFTF)
2.2.1	Electric Generating Sets
3.1.1	Radioisotope Fueled Thermoelectric Generator (RPG)
4.1.1	Photo Voltaic Cell
4.2.1	Wind Generators

POWER SOURCE INFORMATION SHEET

TYPE: Leclanche (Carbon-Zinc) Dry Battery

DESCRIPTION: The Leclanche system, named after its inventor and now commonly referred to as carbon-zinc (dry cell), is the most widely produced type of primary cell. Its wide use can be attributed to its low cost and to the wide variety of shapes, sizes, and voltage levels readily available.

The negative electrode is zinc plate and the electrolyte is a mixture of ammonium chloride and zinc chloride solidified with starch or infiltrated into paper to prevent flow. The positive electrode is a solid, molded mixture of manganese dioxide and acetylene black.

FEATURES: The general features of the zinc-carbon cell are

(a) popular and inexpensive;

(b) internationally standardized;

(c) broad working current and temperature ranges;

(d) trouble-free handling;

(e) longer service when used intermittently than when continuously used;

(f) limited efficiency at low temperatures.

SUGGESTED APPLICATIONS: Typical uses for these batteries include flashlights, portable radios, lanterns, toys, photographic equipment, bicycle lights and horns, tape recorders, radio-controlled models, and many types of industrial electronic instruments.

SPECIFICATIONS

	CYLINDRICAL TYPE
Capacity available at 32-hr. rate (a.h.)	0.35 - 21
Open circuit voltage (v)	1.55 - 1.70
Open circuit battery voltage (based on 1.5 volts/cell)	1.55 - 45.0
Nominal operating voltage (v)	1.25
Recommended discharge temperature (°F)	65 - 85
Functional discharge temperature (°F)	0 - 120
Recommended storage temperature (°F)	-40 - 75
Permissible storage temperature (°F)	-40 - 111
Self discharge rate at room temperature (%/mo.)	1.0 - 1.5
Watt hr./lb. at 32-hr. rate	15.5 - 34[1]
Watt hr./cu.in. at 32-hr. rate	0.9 - 2.7[1]
Electrolyte	Aqueous solution of zinc chloride and ammonium chloride.
Electrochemical equation	$4Zn + 8MnO_2 + 8H_2O + ZnCl_2 \rightarrow 4Mn_2O_3 \cdot H_2O + ZnCl_2 \cdot 4Zn(OH)_2$

SAFETY NOTE: The zinc case of the Leclanché battery is consumed during the processes of discharge; this deterioration may cause leakage and consequent corrosion of the equipment in which it is housed.

[1] 32-hr. rate, continuous drain, at 1.0v cutoff

POWER SOURCE INFORMATION SHEET

TYPE: Alkaline-Manganese Dioxide Battery

DESCRIPTION: The alkaline-manganese dioxide system differs from the Leclanche in several ways. The most imortant difference is the electrolyte alkaline cells use a solution of potassium hydroxide, an electrolyte more conductive than the zinc chloride-ammonium chloride solution of the Leclanche cell. The anode is also structured differently. Although zinc is the anodic material in both systems, in the Leclanche cell the anode is either the case material itself, or in sheet form (wafer cells); whereas in the alkaline cell, the anode is composed of amalgamated granular zinc.

The open circuit voltage of an alkaline cell is about the same as that of the Leclanche cell, about 1.5 volts. At low current drains they are essentially the same for a given cell size, but at high discharge rates the alkaline cell is markedly superior. The alkaline cell is also superior to the Leclanche at low temperatures.

FEATURES: At high current drain (0.300 amperes), the service life of the alkaline cell is approximately 4.3 times greater than that of the Leclanche.

Alkaline cells have better low temperature discharge characteristics than Leclanche cells, even better than those that employ special low temperature electrolytes.

SUGGESTED APPLICATIONS: Typical applications of alkaline cells are in transistor pocket radios, electric shavers, electronic photoflash, cameras, radio-controlled models, toys, cassette players and recorders, and heavy duty lighting.

SPECIFICATIONS

Capacity available at 32-hr. rate (a.h.)	0.580 - 10.0
Open circuit voltage (v)	1.50
Open circuit battery voltage (v) (as integral single unit assemblies)	1.5, 3.0, 4.5
Nominal operating voltage (v)	1.25
Recommended discharge temperature (°F)	65 - 115
Functional discharge temperature (°F)	-4 - 130
Recommended storage temperature (°F)	-40 - 80
Permissible storage temperature (°F)	-40 - 120
Self discharge rate at room temperature (%/mo.)	0.8 - 0.9
Watt hr./lb. at 32-hr. rate	33 - 38
Watt hr./cu.in. at 32-hr. rate	3.8 - 3.9
Electrolyte	Potassium hydroxide solution
Electrochemical equation	$Zn + 2MnO_2 \rightarrow ZnO + Mn_2O_3$
Nominal size range	Diameter: 0.41" to 0.66" Height: 1.11" to 2.37"
Nominal weight range (lbs.)	0.02 - 0.33

POWER SOURCE INFORMATION SHEET

TYPE: Lithium Inorganic Battery

DESCRIPTION: The lithium inorganic cell differs from the lithium organic or sulphur dioxide cell[1] in that the cathode reactant [liquid oxyhalides, such as thionyl chloride ($SOCl_2$) or sulfuryl chloride (SO_2Cl_2)] also serves as the sole solvent for the electrolyte [usually lithium tetrachloroaluminate ($LiAlCl_4$)].

As in the sulphur dioxide cell, a low weight, high surface area, carbon positive electrode acts as a catalyst for the reduction of the cathode reactants, thus permitting the cell reaction to proceed. Since the solvent acts as the "fuel" for the cell, there is no need for a separate supply of cathode reactants, and the attendant result is a greatly reduced cell weight and increased specific energy.

FEATURES: Current laboratory versions of the lithium-thionyl chloride cell exhibit specific energies of the order of 500 watt hours per kilogram, more than 50 percent higher than previous lithium-sulphur dioxide cells and more than eight times higher than the common flashlight battery. Other features include improved low temperature operation (down to -45° C) and voltage stability.

APPLICATIONS: Oceanographic instrumentation, sonar systems, biotelemetry devices, undersea weapons, small undersea vehicles, meteorological instrumentation, field communications.

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[1] See Lithium Organic Cell Information Sheet Identifier 1.1.4

SPECIFICATIONS

Voltage output (v)	3.64 ± 0.02 v
Capacity range (a.h.)	.065 - 10.00[2]
Discharge current range (a.h.)	.001 - 1.0A maximum
Voltage cutoff (v)	3.00
Nominal volume range (cm^3)	0.45 - 55.77
Nominal weight range (gms)	0.940 ± 0.02 - 96 ± 2
Cost	Competitive with alkaline manganese

[2] Experimental large cells (150 a.h.) have been built and successfully tested, demonstrating the ability to scale-up such cells

POWER SOURCE INFORMATION SHEET

TYPE: Lithium Organic Cells

DESCRIPTION: The lithium organic battery contains a lithium anode, a carbon cathode and an organic electrolyte containing liquid sulphur dioxide. The liquid sulphur dioxide is the depolarizer. The cells are constructed by winding rectangular strips of anode-separator-cathode-separator stacks into a cylindrical roll, which is then placed in a nickel-plated steel can. This method increases the surface area of the electrodes and gives the cells a high current capability.

FEATURES: Very high power densities; operates at both extremely low and high temperatures; long shelf life; high working voltage; high current capabilities; flexible design.

However, because of its high operating voltage, products may have to be redesigned to accommodate one-half the number of batteries normally utilized, or use adapters (dummy cells) to fill the void.

APPLICATIONS: Oceanographic instrumentation, sonar systems, biotelemetry devices, undersea weapons, small undersea vehicles, meteorological instrumentation, field communications.

SPECIFICATIONS

Nominal cell voltage (v)	2.8
Energy density (watt hr./cu. in.)	5 - 7
(watt hr./lb.)	80 - 145
Shelf life (years)	>5 (70°F)
	>1 (130°F)
Nominal storage temperature (°F)	-40 - 160
Operating temperature range (°F)	-65 - 160
Mechanical integrity	Excellent
Voltage regulation	Excellent
Cost	Competitive with alkaline manganese.

POWER SOURCE INFORMATION SHEET

TYPE: Mercuric Oxide Battery

DESCRIPTION: The mercuric oxide system is notable for its flat discharge curve (voltage vs time), excellent charge retention, and high energy-to-volume ratio. No marked difference in capacity is observable between intermittent and continuous service.

Two types of cells are manufactured; one with an open-circuit voltage of 1.40 volts, the other with an open-circuit voltage of 1.35 volts. In both types of cells the anode and general construction features are identical, the only difference being in the cathode materials. The higher voltage cells use manganese dioxide in combination with mercuric oxide and micronized graphite, whereas in the lower voltage application, manganese dioxide is not used.

FEATURES: The most outstanding features of the mercuric oxide system are its relatively constant discharge curve (voltage vs time) throughout a wide current drain range, and its excellent energy to volume ratio.

SUGGESTED APPLICATIONS: Typical uses for these batteries are in hearing aids, alarm systems, radiation detection devices, portable test apparatus, scientific and clinical laboratory instruments and potential standards.

SPECIFICATIONS

	MERCURIC OXIDE
Capacity available at 32-hr. rate (a.h.)	0.075 - 14.0
Open circuit voltage (v)	1.35
Open circuit battery voltage (v)	2.70 - 9.45
Nominal operating voltage (v)	1.25
Recommended discharge temperature (°F)	65 - 130
Functional discharge temperature (°F)	30 - 130
Recommended storage temperature (°F)	-10 - -80
Permissible storage temperature (°F)	-10 - -130
Self-discharge rate at room temperature (%/mo.)	0.8 - 0.9
Watt hr./lb. at 32-hr. rate	37 - 48
Watt hr./cu.in. at 32-hr. rate	4.7 - 6.0
Electrolyte	Concentrated aqueous solution of potassium hydroxide
Electrochemical equation	$HgO + Zn \rightarrow Hg + ZnO$
Nominal size range	Diameter: 0.310" to 0.66" Height: 0.140" to 2.3"
Nominal weight range (lbs.)	0.0013 to 0.370

POWER SOURCE INFORMATION SHEET

TYPE: Zinc-Air Cell

DESCRIPTION: The zinc-air system is a comparatively recent development in the primary battery field. It has the highest energy density per unit weight of all the aqueous primary systems, and its energy density on a volume basis is up to two times greater than that of the mercuric oxide system. Like the Leclanche and the mercuric oxide cell, zinc is used as the anode. However, the cathode is not consumed during discharge. Oxygen from the air provides the oxidant for its operation.

In the zinc-air system, the cathode structure does not change to any marked degree with capacity. As a consequence, the capacity of a particular cell is governed almost exclusively by the total zinc content of the anode. This means that the greater the capacity of the cell, the greater the energy density, based on both weight and volume. For example, a 3 ampere-hour cell has an energy density of about 80 watt-hours per pound, while a 25 ampere-hour cell may have an energy density of about 150 watt-hours per pound.

FEATURES: Zinc-air cells provide the following desirable features:

(a) extremely small self-discharge;

(b) easy maintenance-free operation;

(c) flat discharge voltage characteristics, stable voltage obtainable;

(d) small size, light weight, great economy;

(e) large capacity and long-life.

APPLICATIONS: Typical zinc-air cell applications include: Oceanographic instrumentation, sonar systems, biotelemetry devices, undersea weapons, small undersea vehicles, meteorological instrumentation, field maintenance.

SPECIFICATIONS

Capacity available at 25-hr. rate (a.h.)	3 - 25
Open circuit voltage (v)	1.45
Nominal operating voltage (v)	0.90 - 1.30
Recommended discharge temperature (°F)	50 - 100
Functional discharge temperature (°F)	-5 - 120
Recommended storage temperature (°F)	-80 - 100
Self discharge rate at room temperature (%/mo.)	0.2 - 1.0
Watt hr./lb. at 25-hr. rate	80 - 150
Watt hr./cu.in. at 25-hr. rate	10 - 15
Electrolyte	Potassium hydroxide
Electrochemical equation	$Zn + 1/2\text{-}O_2 \rightarrow ZnO$

POWER SOURCE INFORMATION SHEET

TYPE: Lead-Acid, Automotive

DESCRIPTION: The lead acid-automotive system has been specifically designed for vehicle starting and applications that require the delivery of high levels of power throughout a wide temperature range.

A comparatively recent innovation has been the introduction of a polypropylene container as a replacement for the traditional hard rubber case in automotive batteries. The advantages of this material are: thinner case walls which permit the use of a greater number of plates in a given volume, thus increasing the high-rate discharge capability; substantially improved impact resistance; and less weight which improves the energy density of the system.

The open circuit voltage of a lead-acid automotive battery ranges between 2.05 and 2.10 volts, and the specific gravity of the sulfuric acid electrolyte ranges from 1.265 to 1.300. For most applications the specific gravity of the acid is 1.265.

Automotive lead-acid cells differ from motive power and stationary units by naving thinner plates. By using thin plates and thin separators, more plates can be accommodated in a given volume. Thus by using as large a surface area as possible, larger currents can be drawn at higher voltage levels, even at low temperatures.

APPLICATIONS: Lead-acid automotive typical applications include automobile starting, lighting, and ignition (SLI) systems for diesels, buses, and trucks.

SPECIFICATIONS

Capacity available at 20-hr. rate (a.h.)	33 - 340
Open circuit voltage (v)	2.05 - 2.10
Open circuit battery voltage (v)	6, 8, 12
Nominal operating voltage at 20-hr. rate (v)	1.98
Nominal end-of-charge voltage at 20-hr. rate (v)	2.53
Recommended charge rate	C/20 or higher - do not exceed electrolyte temperature of 1.25°F or overcharge recommendation
Recommended overcharge at 20-hr. rate (%)	5 - 40
Recommended discharge temperature (°F)	70 - 90
Functional discharge temperature (°F)	-40 - 140
Optimum charge temperature (°F)	50 - 115
Permissible charge temperature (°F)	-40 - 125
Recommended trickle charge/float/finishing rate	Trickle charge C/100 - continuous overcharging
Recommended storage temperature, wet (°F)	-40 - 115
Permissible storage temperature, wet (°F)	-40 - 120
Recommended storage temperature, dry (°F)	-40 - 115
Self discharge rate at room temperature, wet (%/mo.)	5 - 11
Self discharge rate at room temperature, dry (%/mo.)	1 - 5
Watt hr./lb.	12.7 - 21.8
Watt hr./cu.in.	0.79 - 1.6
Impedance (ohms)	0.0010 - 0.0024
Cycle life (cycles)	150 - 250
Electrolyte	Sulfuric acid solution - specific gravity 1.265 - 1.300
Electrochemical equation	$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$

POWER SOURCE INFORMATION SHEET

TYPE: Lead-Acid, Stationary

DESCRIPTION: Stationary batteries are specifically designed for float applications, that is, as standby power in the event of a prime power failure, or for switch gear applications. The batteries are maintained at a full state-of-charge, ready-for-use condition, generally by floating at a constant voltage source set at 2.17 volts per cell. The specific gravity of all stationary batteries is between 1.210 and 1.220 at 77°F; and the open-circuit voltage is between 2.06 and 2.07 volts per cell.

There are three types of stationary cells manufactured; those with grids of lead-calcium, those with lead-antimony grids, and the Plante type.

The calcium type cell is available in a capacity range of 50 to 2550 ampere-hours; the Plante, from 8 to 996 ampere-hours, and the lead-antimony type, from 10 to 800 ampere-hours. All stationary cells are rated at the 8-hour discharge rate at 77°F, to a cutoff voltage of 1.75 volts.

APPLICATIONS: There are two basic applications for stationary batteries; in the switch gear field, and as standby or operational power in the communications field. Another application, however, is for standby power or emergency lighting in commercial buildings.

POWER SOURCE INFORMATION SHEET

TYPE: Sealed Nickel-Cadmium (NICAD)

DESCRIPTION: Operation of a nickel-cadmium cell involves little or no change in electrolyte concentration. The active material of both electrodes, in both charged and discharged states, is relatively insoluble in the alkaline electrolyte. Because of these and other properties, nickel-cadmium cells are characterized by long life in both cycle and standby operation, and by a relatively flat voltage profile within a wide discharge current range.

Nickel-cadmium batteries are available in button, cylindrical, and rectangular form.

FEATURES: A few of the important features of the nickel-cadmium systems are as follows:

(a) maintenance-free operation;

(b) high-rate charging capability;

(c) high-rate discharge capability;

(d) constancy of discharge voltage;

(e) capability of withstanding extended overcharge;

(f) excellent cycle life;

(g) moderate self-discharge rate.

APPLICATIONS: Typical applications of nickel-cadmium batteries include communications equipment, instruments, photographic equipment, power tools, shavers, hearing aids, alarms (standby), computers, line concentrators, etc.

SPECIFICATIONS

	CYLINDRICAL	RECTANGULAR
Capability available at 5-hr. rate (a.h.)	0.100 - 7.0	11 - 23
Open circuit voltage (v)	1.30	1.30
Nominal operating voltage (v at 5-hr. rate)	1.25	1.25
Nominal end-of-charge voltage (v)	1.48	1.48
Recommended charge rate	C/10	C/10
Recommended discharge temperature (°F)	65 - 85	65 - 85
Functional discharge temperature (°F)	-40 - 140	-5 - 115
Optimum charge temperature (°F)	65 - 85	65 - 85
Permissible charge temperature (°F)	32 - 115	32 - 115
Recommended trickle charge rate	C/20	C/100
Recommended storage temperature, wet (°F)	-40 - 80	-40 - 80
Permissible storage temperature, wet (°F)	-40 - 120	-40 - 140
Self discharge rate at room temperature wet (%/mo.)	10 - 15	5 - 8
Self discharge rate at room temperature dry (%/mo.)	N/A	N/A
Watt hr./lb.	8.3 - 19.0	7.4 - 9.2
Watt hr./cu.in.	0.85 - 2.20	0.62 - 0.73
Impedance (ohm)	0.006 - 0.70	0.009 - 0.02
Cycle life (cycles)	250 - 10,000	250 - 10,000
Electrolyte	Potassium hydroxide (concentration 25% to 35%)	
Electrochemical equation	$Cd + 2NiO(OH) + 2H_2O \rightarrow Cd(OH)_2 + 2Ni(OH)_2$	
Nominal size range (in.)	Length: 0.44 - 3.65 Height: 0.20 - 4.96	
Nominal weight range (lbs.)	0.04 - 50.0	

POWER SOURCE INFORMATION SHEET

TYPE: Silver-Zinc Battery

DESCRIPTION: The silver-zinc cell has the highest energy density of any commercially available secondary cell. Also, it has the least voltage drop during discharge. Silver-zinc cells can operate efficiently at extremely high discharge rates (5C to 10C), and have excellent dry charge retention when properly sealed from atmospheric oxygen. The high-rate discharge capability of the silver-zinc system results primarily from the excellent conductivity of both the electrode material and the grid, because of close electrode spacing, and because of constant electrolyte conductivity. Charge acceptance of silver-zinc cells at moderate rates (C/10 to C-15) is very good, exceeding that of any other secondary cell. Charging should, however, be terminated when the voltage reaches 2.05 volts per cell, and overcharging is not recommended.

As in other alkaline systems, a decrease in operating voltage and effective discharge rates is experienced with the silver-zinc cell at low temperatures; however, by incorporating special design features cells can be fabricated to operate at moderate rates at temperatures as low as -65°F.

The silver-zinc cell uses silver oxide as the positive electrode, zinc as the negative electrode, and potassium hydroxide (generally 40%) as the electrolyte.

FEATURES: Silver-zinc cells incorporate the following features:

(a) very high energy density;

(b) low voltage drop during discharge;

(c) efficiency at extremely high discharge rates;

(d) excellent dry charge retention (when properly sealed).

APPLICATIONS: Typical applications of silver-zinc cells include deep submersible equipment, power for submarines, radio equipment, torpedo propulsion, and unmanned target drones.

SPECIFICATIONS

	LOW RATE	HIGH RATE	FAST ACTIVATING	PRIMARY
Capability available at 1-hr. rate (a.h.)	1 - 140	1 - 150	1 - 180	1.5 - 220
Open circuit voltage (fully charged) (v)	1.86	1.86	1.86	1.86
Nominal operating voltage (v)	1.45	1.45	1.45	1.45
Nominal end-of-charge voltage (v)	2.05	2.05	2.05	N/A
Recommended charge rate	8 hr. rate to 2.00 v then reduced to 20-hr. rate until voltage reaches 2.05 v			
Recommended overcharge (%)	Overcharge or trickle charging are not recommended			N/A
Recommended discharge temperature (°F)	50 - 90	50 - 90	50 - 90	50 - 90
Functional discharge temperature (°F)	-40 - 140	-40 - 140	-40 - 140	-40 - 140
Optimum charge temperature (°F)	50 - 90	50 - 90	50 - 90	N/A
Permissible charge temperature (°F)	32 - 120	32 - 120	32 - 120	N/A
Recommended storage temperature, wet (°F)	32 - 90	32 - 90	32 - 90	32 - 90
Permissible storage temperature, wet (°F)	-50 - 160	-50 - 160	-50 - 160	-50 - 160
Recommended storage temperature, dry (°F)	32 - 90	32 - 90	32 - 90	32 - 90
Self discharge rate at room temperature wet (%/mo.)	2 - 5	2 - 5	2 - 10	N/A
Self discharge rate at room temperature dry (%/mo.)	0.5 - 1.0	0.5 - 1.0	1.0 - 2.0	5 - 10
Watt hr./lb. at 1-hr. rate	32 - 60	38 - 66	36 - 72	40 - 80
Watt hr./cu.in. at 1-hr. rate	1.66 - 4.20	1.95 - 4.61	2.20 - 5.22	2.37 - 6.51
Cycle life (cycles)	25 - 50	10 - 20	2 - 5	1
Electrolyte	Concentrated solution potassium hydroxide			
Electrochemical equation	$Ag_2O_2 + 2Zn + H_2O \quad 2Ag + 2Zn(OH)_2$			
Nominal size range (in.)	Weight - 1.08 - 5.20; Length - 0.54 - 3.36; Height - 1.56 - 7.02			
Nominal weight range (lbs.)	0.047 - 9.35			

POWER SOURCE INFORMATION SHEET

TYPE: Thermoelectric Generators, Gas-Fired (GFTG)

DESCRIPTION: The basic theory behind the operation of thermoelectric generators is the thermocouple effect (also known as the Seeback effect). A voltage will be generated when one junction between two dissimilar metals is hotter than the other junction. This generated voltage is proportional to the temperature difference between the cold and the hot ends on the semiconductor thermoelectric material.

Heat in the thermoelectric generator is supplied by the combustion of propane, butane, or natural gas, in a low temperature, catalytic process, which is extremely stable and safe. The noble catalyst bed remains active down to low temperatures (about 300°F), sufficient to burn the gas mixture. Combustion takes place in completely-enclosed chambers with long intake and exhaust manifolds.

FEATURES: Economy – no other form of providing electricity compares within the GFTG power range.

Reliability – GFTG's will operate for years without maintenance, service, or repair. Periodic refueling is all that is required.

All weather and temperature – GFTG's are normally installed without enclosures. They are fully reliable at sub-zero or 150°F temperatures.

APPLICATIONS: Typical applications of gas-fired thermoelectric generators are in aeronautical and marine navigational aids, communications equipment, data systems, telecontrols, and railway signals. The GFTG is a first choice for a reliable, unattended, remote power source.

SPECIFICATIONS

	VOLTAGE	AMPERAGE	WATTAGE
Power options (minimums)	4.8	2.1	10
	9.6	2.1	20
	14.4	2.1	30
	19.2	2.1	40
	24.0	2.1	50
	28.8	2.1	60
	33.6	2.1	70
	38.4	2.1	80
	43.2	2.1	90

Fuel options	Propane, butane, or natural gas
Fuel consumption	Propane & butane: 11.2 - 100.8 lbs./wk. Natural gas: 0.23 - 2.07 gas MCF/wk.
Weight range (lbs.)	3 - 189
Size range (in.)	Height - 17; Weight - 11 to 25; Length - 19 to 47

POWER SOURCE INFORMATION SHEET

TYPE: Electric Generating Sets

DESCRIPTION: Mobile electric generating sets are available from many manufacturers in sizes ranging from 500 watts to 500 kw. They can be obtained in a variety of engine types, such as gas (air-cooled), gas (liquid-cooled), LNG (air-cooled), LNG (liquid-cooled), diesel (air-cooled), diesel (liquid-cooled), and marine versions of most of these types.

These units are ideally suited for portable, standby/emergency, mobile, prime mover and marine applications.

FEATURES: Electric generating units are available in a wide range of sizes. They are rugged and very reliable, and under normal operating conditions require very little maintenance.

APPLICATIONS: Electric generating sets are used extensively to power lighting, communications equipment, heating, air-conditioning, freezers, fans, pumps, elevators, etc.

SPECIFICATIONS

Power range (kw)	0.5 - 500 120 @ 1 ϕ 120/240 @ 3 ϕ 240 @ 3 ϕ 120/208 @ 3 ϕ
Fuel types	Gasoline, diesel, LNG, natural gas
Fuel consumption (gal. per 24 hrs.)	Gas/LPG/natural gas: 6.0 - 585 Diesel: 9.0 - 871.2
Size range (in.)	Weight: 14 - 55; Height: 17 - 98 Length: 19 - 142
Weight range (lbs.)	98 - 10,500

POWER SOURCE INFORMATION SHEET

TYPE: Radioisotope Fueled Thermoelectric Generator (RPG)

DESCRIPTION: All RPG's currently used for terrestrial and oceanographic applications use a strontium titanate fuel encapsulated in a nickel alloy (Hastelloy C) capsule. Some RPG's at the lower power levels ($\lessdot 1$ watt) use plutonium-238 as fuel. Plutonium-238 offers many advantages (e.g., an 89 year half-life and lower shielding requirements).

The basic components of an RPG are

(a) a fuel capsule containing the encapsulated Sr^{90} or Pu^{238} fuel;

(b) a thermopile containing the thermoelectric conversion elements;

(c) thermal insulation to maintain the proper thermal balance for best energy conversion efficiency;

(d) biological shielding to minimize external radiation;

(e) a casing or outer housing to protect the components against adverse environment and stress.

A power conditioner is often used as an auxiliary component which converts the low voltage DC power from the thermoelectric array to the required AC or DC voltage levels.

A power storage system consisting of nickel-cadmium batteries and charging equipment is also often used with RPG's to provide reserve capacity for peak power loads.

These five components are required for all systems from the milliwatt to kilowatt range. Some small RPG's using Pu^{238} require little or no shielding for some applications.

FEATURES: Provides constant reliable electrical power from less than one watt to 100 watts for periods of time from 1-20 years, unattended.

APPLICATIONS: Radioisotope Power Generators (RPG's) are being used in a variety of terrestrial, hydrospace and aerospace applications with exceptional success. Commercially available RPG's provide silent, steady power outputs that range from micro-watts to 100-watts. They will operate unattended for periods of 5-20 years in most ambient environments, including ocean depths of 20,000 feet.

SPECIFICATIONS

U.S. NAVY RPG INVENTORY

POWER in WATTS	APPLICATION	WEIGHT lbs.	DIMENSIONS diameter x height inches	PRESSURE psi	RPG NUMBER
0.072	land/water	350	8 x 22	4400	4
1.0	land/water	835	14 x 18	10000	3
1.4	land/water	840	14 x 18	10000	17
1.5	land/water	845	14 x 18	10000	5
1.6	land/water	840	14 x 18	10000	15
1.6	land/water	840	14 x 18	10000	16
1.6	land/water	840	14 x 18	10000	18
1.8	land/water	750	14 x 15	10000	33
1.8	land/water	750	14 x 15	10000	39
1.9	land/water	750	14 x 15	10000	34
1.9	land/water	750	14 x 15	10000	35
1.9	land/water	750	14 x 15	10000	36
1.9	land/water	750	14 x 15	10000	37
1.9	land/water	750	14 x 15	10000	38
1.9	land/water	750	14 x 15	10000	40
2.1	land/water	2800	24 x 26	1500	2
9.4	land/water	1500	18 x 18	500	27
9.4	land/water	1500	18 x 18	500	28
10.1	land/water	1500	18 x 18	500	25
10.3	land/water	1500	18 x 18	500	26
10.5	land/water	645	16 x 25	10000	42
10.5	land/water	645	16 x 25	10000	43
11.6	land/water	3150	24 x 29	1670	24
12.8	land/water	1470	24 x 42	6000	7
15.8	land	3000	35 x 30	atm	1
28.0	land/water	4170	26 x 31	10000	11
28.0	land/water	4170	26 x 31	10000	12
28.0	land/water	4170	26 x 31	10000	13
33.0	land/water	2000	25 x 35	6000	6
33.2	land/water	3000	27 x 30	1000	9
34.0	land/water	1400	23 x 27	500	21
34.9	land/water	3000	27 x 30	1000	10
35.6	land/water	3000	27 x 30	1000	8
35.6	land/water	1400	23 x 27	500	23
36.0	land/water	1280	23 x 27	500	14
37.0	land/water	1400	23 x 27	500	22
37.7	land/water	1400	23 x 27	500	19
37.8	land/water	1400	23 x 27	500	20
44.9	land/water	4170	26 x 31	10000	32
45.6	land/water	4170	26 x 31	10000	29
46.1	land/water	4170	26 x 31	10000	30
47.9	land/water	4170	26 x 31	10000	31
60.0	land	1200	24 x 32	atm	44
146.0	land/water	2724	28 x 35	500	41
THE FOLLOWING RPG IS UNDER DEVELOPMENT				data as of June 1973	
1/2	water	5	2 x 6		

[1] For additional information, contact: The Nuclear Power Division, Naval Facilities Engineering Command, 200 Stovel Street, Alexandria, Virginia 22332 – (202) 325-0410.

POWER SOURCE INFORMATION SHEET

TYPE: Photo-Voltaic Cell

DESCRIPTION: The direct conversion of solar energy to electrical energy has been successfully accomplished by solar cells made from inorganic semiconductors (silicon, cadmium sulfide, cadmium telluride). Solar cell generator outputs can range from a few milliwatts up to many kilowatts. The outstanding photovoltaic device today is the silicon p-n junction. The primary use of this converter has been in space, where it has demonstrated good efficiency, long life, and exceptional reliability.

The major shortcoming of the silicon solar cell for terrestrial applications has been its high cost ($100/peak-watt). This high cost has been due to the extreme purity required of the starting material and on the low yields and high processing costs from handling single crystal material in a series of batch-processing steps.

An actual system for marine environment use would have to be sized to account for: diurnal variation of solar output, cloud cover, varying incident intensity due to seasonal changes and latitude effects, occlusion of cells from salt deposits, bird droppings, ice and snow, and degradation or failure of some cells. These combined effects would require the usable solar array to be quite large in comparison with the size needed if based only on maximum output.

FEATURES: In general, solar cells may be used economically where power requirements are low, the fuel costs of alternative systems are high, the site location is far from roads or electric power distribution systems, and the insolation levels are high. Other features include

(a) No physical parts are consumed or change chemically. Long battery life with hardly any efficiency loss.

(b) Output current is proportional to incident energy, but output voltage is relatively independent of change in incident energy.

(c) Converts radiant solar energy directly and efficiently into electrical energy.

APPLICATIONS: Photo-voltaic cells are presently used in unmanned lighthouses, navigation beacon and buoy lights, satellites, microwave relay stations, and meteorological observation stations.

SPECIFICATIONS

	TYPICAL CHARACTERISTICS	
Power input:	Solar Isolation	Solar Isolation
Power output (under peak solar conditions):	14 V.D.C.	14 V.D.C.
volts	Nominal 12 volt	Nominal 12 volt
current	300 milliamps	600 milliamps
power	3.9 watts	7.8 watts
Ampere hours/week:	12.6 a.h.	25.2 a.h.
Dimensions: (approximate)		
length	19 3/8″	23 1/4″
width	16″	16 1/2″
height	2 3/8″	1 3/8″

POWER SOURCE INFORMATION SHEET

TYPE: Wind Generators

DESCRIPTION: Wind generators have recently become a competitive electric power supply in locations where a constant wind force can be utilized. The Dutch navy employs small 25-100 watt units in conjunction with lead-acid batteries on buoys and beacons in the North Sea. Scripps Institute of Oceanography also has some limited experience with the use of wind generators.

Wind generators are capable of extracting approximately 5 to 7 percent of the wind energy passing through the propeller in the form of electricity. Since the wind cannot be expected to blow steadily, provision is usually made for energy storage – generally with lead-acid or nickel-cadmium batteries. The 50-100 watt system developed by Scripps is powered by a five-foot diameter impeller blade and is capable of producing up to 200 watts of power at wind speeds of 40 mph. The power for different size propellers and wind speeds may be approximated by the following expression:

$$P = 3.25 \times 10^{-6} D^2 V^3$$

P = watts
D = inches
V = miles per hour.

SPECIFICATIONS

Nominal power range (va @ 28v)	0 - 4100
Nominal output voltage (v)	24 (with associated accumulator cells)
or	220/380 (50 Hz)
Wind speed at start of charge (mph)	9.8 - 13.1
Nominal wind speeds required (mph)	22.9 - 24.6
Axial force for wind speed of 125 mph (#)	110 - 1432
Nominal charging current (a)	1.1 - 40
Propeller diameters (ft.)	2.95 - 16.4
Machine length o/a (ft.)	3.7 - 20.6
Weight (lbs.)	26.4 - 441

[1] Wind speed $\geq$ 15 mph.

APPENDIX D
REPRESENTATIVE BUOY STABILITY ANALYSIS

D1. INTRODUCTION

The motion and resulting stability of freely floating, constrained or unconstrained bodies in the ocean is a highly dynamic problem, the scope of which is beyond the level of effort presented here. However, under certain simplifying assumptions, a static analysis may be conducted to evaluate the stability of a representative buoy system under environmental loads due to winds, waves, and ocean currents.

In the remainder of this section, the static analysis assumptions are discussed and the representative buoy is described. Section D2 defines typical environmental parameters, and equations for the forces, and moments acting on the representative buoy are developed in section D3. Finally, in section D4, the stabilities of three preferred buoy designs are estimated.

D1.1 Static Analysis Assumptions

For the static analysis, the following assumptions are implied:

1. For time scales corresponding to surface gravity wave periods of several seconds, and for length scales corresponding to the dimensions of the representative buoy, the wind and current are assumed to be steady, uniform, and horizontal. Furthermore, since current speeds are typically 1-2 orders of magnitude less than wind speeds, a coordinate system fixed with the moving current is assumed. This essentially eliminates any contribution to the overall force acting on the representative buoy by the current.

2. Waves consist of linear, harmonic disturbances in a two-dimensional vertical plane, resulting in orbital motions of the representative buoy. Complications arising from more typical "confused" sea states are neglected. Furthermore, if inertial accelerations are neglected, the vertical component of motion (heave) is determined by the vertical displacement of the ocean surface, which can be specified for a given sea state. Hence, only the horizontal component of the motion need be considered in relation to the overall balance of forces determining the stability (i.e., the righting moment) of the system. These horizontal components reach a maximum at the crest and trough of the wave, where the orbital motion is entirely horizontal, and decrease in magnitude exponentially with increasing depth. The wave load on the system is therefore assumed to be the magnitude of the orbital velocity, applied in the horizontal direction opposed to that of the wind load, and resulting in the maximum torque on the system ("worst-case").

3. The loading forces are applied to the representative buoy as if it were rigid and motionless. However, in the resolution of forces acting on the system, rotation about a horizontal axis will be allowed so that an equilibrium may exist between moments generated by buoyancy forces, weight of system components, and horizontal loads.

The above assumptions necessarily compromise the validity of the static analysis, particularly with regard to nonlinear interactions and system accelerations. However, the static analysis should provide some insight to the magnitude of the dynamic stability problem in "worst-case" situations.

D1.2 Representative Buoy Description

The representative buoy system (pendulous spherical buoy) is schematically shown in figure D.1. It consists of a float with a pendulous arm extending downward to form a "ball-in-socket joint" where the float rotates in the ocean support. A ballast weight is suspended from the end of the pendulous arm, well below the effective depth of the surface wave motion, to provide a righting moment when the buoy is tilted. A canister, providing space for electronic components and batteries, protrudes from the base of the float. The buoy supports a cylindrical mast and truncated conical antenna. The three preferred buoy designs are all modifications of this representative buoy.

In accordance with the above assumptions, the stability of this representative buoy shall be examined. Stability is defined with respect to the rotation of the buoy in a two-dimensional vertical plane about the center of the float. This rotation is caused by moments due to the buoyancy and weight of system components, and horizontal wind and wave loads. A "worst-case" is assumed where the wind and maximum wave loads are opposed to one another, creating maximum torque on the system. The specified design criterion is for the antenna to remain upright within ten degrees of vertical for conditions up to and including sea state 6.

D2. ENVIRONMENTAL PARAMETERS

To meet design specifications, the representative buoy system should survive in sea state 8 conditions and give "creditable" performance in sea state 6 conditions. Typical values of environmental parameters for sea state 6 conditions are given in table D-1. The corresponding design wind and wave loading profiles are described in the following subsections.

Table D.1. Typical Values of Environmental Parameters (Sea State 6).

Significant Wave Height (H_s)	5.0 m (=16.4 ft)
Average Wavelength (λ)	60 m (=196.9 ft)
Average Wave Period (T)	7.5 s
Air Density (ρ)	1.23 kg/m^3 (=2.38 $\times 10^{-3}$ slug/ft^3)
Air Viscosity (μ_a)	1.79 $\times 10^{-5}$ kg/m/s (=3.74 $\times 10^{-7}$ lb$\cdot$s/ft^2)
Seawater Density (ρ_w)	1.027 $\times 10^3$ kg/m^3 (=1.99 slug/ft^3)
Seawater Viscosity (μ_w)	1.4 $\times 10^{-3}$ kg/m/s (=2.9 $\times 10^{-5}$ lb$\cdot$s/ft^2)

D2.1 Design Wind Profile

For computational simplicity, a wind profile with a uniform horizontal wind speed of W = 12.9 m/s^{-1} (= 25 knots = 42.2 ft/s^{-1}) is assumed. This profile ignores surface boundary (frictional) and Coriolis effects. The design wind profile is schematically shown in figure D-1.

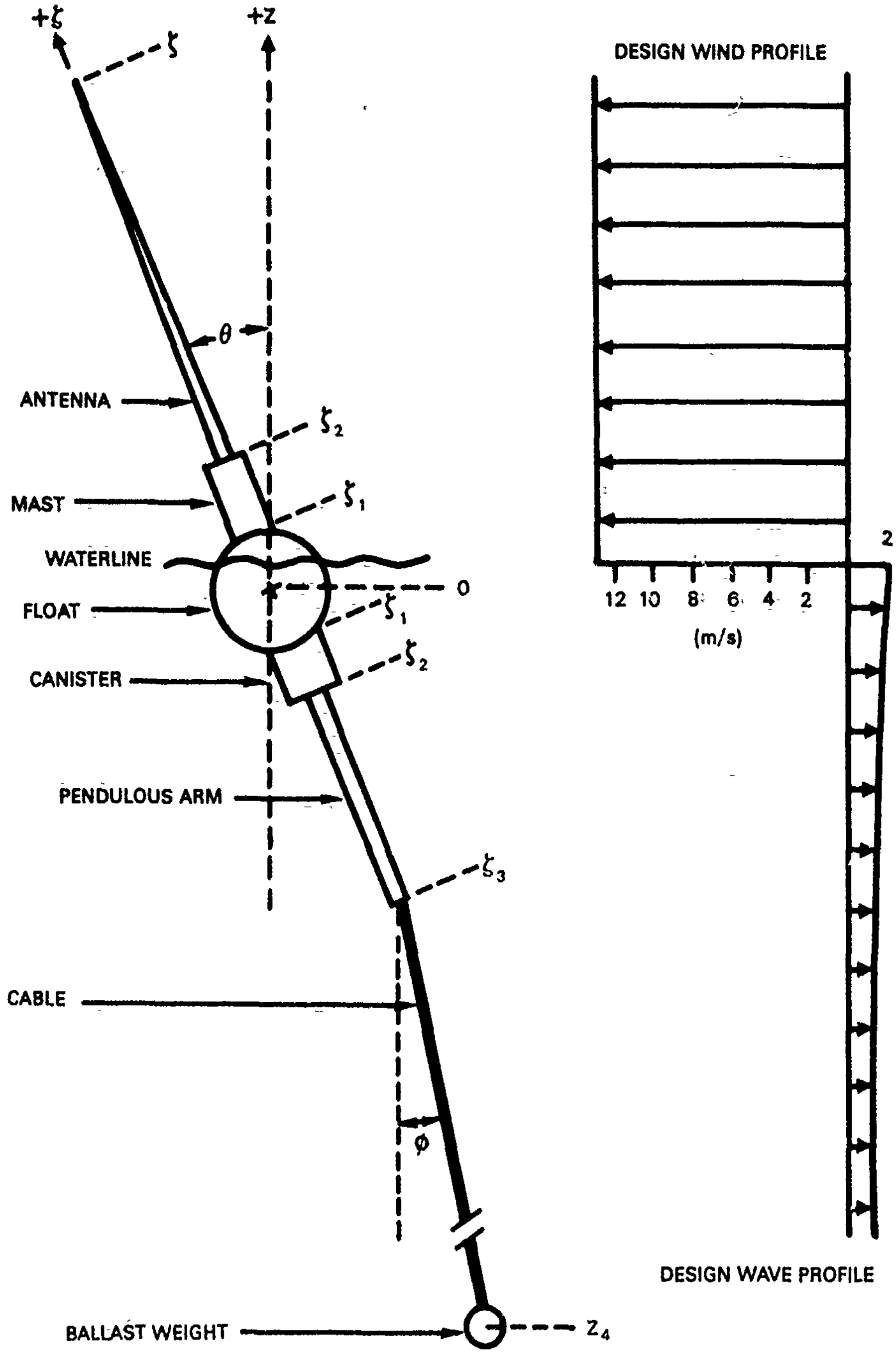

Figure D.1. Representative buoy components and design wind and wave profiles for the stability analysis.

D2.2 Design Wave Profile

The design wave profile is defined as follows. Consider a harmonic surface displacement in the two-dimensional (x, z) plane:

$$\eta = A\cos(kx - \omega t).$$

Here $A = H_S/2$ is the wave amplitude, $k = 2\pi/\lambda$ is the wave number, and $\omega = 2\pi/T$ is the angular frequency. For small amplitude waves, the (u, w) velocity components corresponding to the (x, z) directions are given by

$$u = A\omega \frac{\cosh[k(z + D)]}{\sinh(kD)} \cos(kx - \omega t),$$

$$w = A\omega \frac{\sinh[k(z + D)]}{\sinh(kD)} \sin(kx - \omega t).$$

Here D is the water depth and +z is directed upward. For deep water waves (where $D > \lambda/4$) the expressions for the velocity components simplify to

$$u = A\omega\, e^{kz} \cos(kx - \omega t),\ \ \omega = A\omega\, e^{kz} \sin(kx - \omega t).$$

These are the equations of a circle of radius $A\, e^{kz}$, i.e., water particles move in circular orbits which decrease in diameter exponentially with increasing depth.

The magnitude of the velocity is

$$V = (u^2 + w^2)^{1/2} = A\omega\, e^{kz}.$$

For sea state 6, $A = 2.5$ m, $\lambda = 60$ m, and $T = 7.5$ s, so that $k = 2\pi/\lambda = 0.10\ m^{-1}$ and $\omega = 2\pi/T = 0.84\ s^{-1}$. Therefore,

$$V = 2.09\, e^{(0.1)z}\ m\, s^{-1}\ (= 6.87\, e^{(0.032)z}\ ft\, s^{-1}).$$

The design wave profile is assumed to be the magnitude, V, applied in the horizontal direction, as illustrated in figure D.1.

D3. FORCES AND MOMENTS

The forces and moments acting on the representative buoy are examined in the following subsections. Coordinates are referenced to an origin located at the center of rotation of the buoy with the direction of the buoy axis denoted by ξ. Under equilibrium conditions, this axis will (in general) be tilted at an angle θ to the vertical. The cable and ballast weight are suspended from the end of the pendulous arm at an angle ϕ to the vertical (see figure D-1).

D3.1 Gravitational Body Forces

Every body of mass $m = \int \rho \, dV$ subject to the gravitational field of the earth experiences a downward force (weight) of the magnitude

$$F_w = mg = g \int \rho \, dV.$$

Here $g = 9.8 \text{ m s}^{-2}$ ($= 32.2 \text{ ft s}^{-2}$) is the magnitude of the gravitational acceleration, ρ is the density of the body, and the integral is taken over the volume V of the body. The distributed weight of the body is equivalent to the total weight acting at the center of mass (mass centroid) of the body. For the representative buoy, the distance from the center of rotation to the mass centroid is

$$\zeta = \int \xi \rho \, dV / m.$$

A body immersed in a fluid also experiences an upward force (buoyancy) equal in magnitude to the weight of the fluid displaced by the body; i.e.,

$$F_b = g \int \rho_f \, dV.$$

Here ρ_f is the density of the fluid and the integral is taken over the volume V of the displaced fluid. The center of buoyancy is the mass centroid of the displaced fluid.

For the representative buoy, weight, and buoyancy of individual components will be considered separately. For simplicity, densities will be assumed uniform throughout the component bodies unless otherwise noted.

D3.1.1 Weight. The weight of all buoy components must be considered with the exception of the cable, which is assumed to be neutrally buoyant (i.e., the weight of the cable equals the buoyancy, so that the resultant body force on the cable is zero).

For the *antenna* (frustum of a right circular cone of height $H = \xi_3 - \xi_2$ and bottom and top base radii R_2 and R_3, respectively), the total weight is

$$F_w = g\rho\pi(R_3^2 + R_3R_2 + R_2^2)H/3.$$

The centroidal distance is

$$\zeta = [(3R_3^2 + 2R_3R_2 + R_2^2)\xi_3 + (R_3^2 + 2R_3R_2 + 3R_2^2)\xi_2]/4(R_3^2 + R_3R_2 + R_2^2).$$

Note that for the case where $R_3 = R_2$, the above expressions for the weight and centroidal distance reduce to those for a right circular cylinder.

For the support *mast* (right circular cylinder of height $H = \xi_2 - \xi_1$ and radius R), the total weight is

$$F_w = g\rho\pi R^2 H.$$

The centroidal distance is

$$\zeta = (\xi_2 + \xi_1)/2.$$

For the *float* (sphere of radius R), the total weight is

$$F_w = g\rho(4\pi R^3/3).$$

The vertical distance to the centroid is $\overline{z} = 0$.

For the electronics/battery *canister* (cylinder of height $H = \xi_1 - \xi_2$ and radius R), the total weight is

$$F_w = g\rho\pi R^2 H.$$

The centroidal distance is

$$\zeta = (\xi_1 + \xi_2)/2.$$

For the *pendulous arm* (cylinder of height $H = \xi_2 - \xi_3$ and radius R), the expressions for the weight and centroidal distance are the same as for the canister except that ξ_1 and ξ_2 are replaced by ξ_2 and ξ_3, respectively.

For the suspended *ballast weight* (sphere of radius R) the total weight is

$$F_w = g\rho(4\pi R^3/3).$$

The mass centroid is at the center of the sphere, located at a vertical depth of $\overline{z} = H \cos\phi$ below the end of the pendulous arm, where H is the length of the cable.

D3.1.2 **Buoyancy.** Due to the relatively low density of air compared to seawater, the buoyancies of components above the sea surface are negligible. The cable is assumed to be neutrally buoyant so that its buoyancy need not be considered here.

For the *float* (sphere of radius R and waterline at altitude z_o), the total buoyancy force on the submerged portion of the sphere is

$$F_b = g\rho_w\pi(z_o + R)^2 (2R - z_o)/3.$$

The vertical distance to the centroid is

$$\overline{z} = -3(z_o - R)^2/4(2R - z_o).$$

For the *canister,* the *pendulous arm,* and the *ballast weight,* the volume of displaced seawater is equivalent to the volume of the buoy component. Thus the expressions for the buoyancy force and centroidal distance are the same as given above for the weight except that the density is that of displaced seawater, ρ_w, rather than that of the component body.

D3.2 Environmental Loading Forces

Wind and wave loads are the result of drag produced on a body by the relative flow of the surrounding fluid. The loading function is given by

$$f(\xi) = \tfrac{1}{2}\,\rho_f C_d\, U(\xi)^2\, S(\xi).$$

Here ρ_f is the density of the fluid medium (assumed constant); C_d is a drag coefficient which depends upon the Reynolds number; $U(\xi)$ is the component of the flow velocity perpendicular to ξ; and $S(\xi)$ is the projected frontal area per unit height of the body perpendicular to $U(\xi)$. U and S are assumed to be functions of ξ only. The Reynolds number, $Re = \rho U^* L^*/\mu$ (where U^* is a characteristic velocity, L^* is a characteristic length, and μ is the dynamic viscosity of the fluid medium), is the nondimensional ratio of the inertial force to the viscous force in fluid motion.

The total drag force on the body is

$$F_d = \int f(\xi)\, d\xi.$$

The distributed load along the body is equivalent to the total drag force acting at the center of force (force centroid) of the body. For the representative buoy, the distance from the center of rotation to the force centroid is

$$\zeta = \int \xi f(\xi)\, d\xi \,/\, F_d.$$

D3.2.1 Wind Loads. The wind loading function is distributed over three regions: the upper part of the float, the support mast, and the antenna. For simplicity, any interference of the flow in one region by the flow of the other regions is neglected. The value for the drag coefficient, C_d, must be determined separately in each region from the value of the Reynolds number and the given buoy component shape.

For the *float,* any rotation about the origin is independent of orientation with respect to the vertical. Hence the loading function is integrated with respect to the vertical coordinate, z. Thus the flow component $U(z) = W$, the design wind profile. The projected frontal area is that of a segment of a circle of radius R and hence the function $S(z) = 2(R^2 - z^2)^{1/2}$. The total drag force on the exposed portion of the float is therefore

$$F_d = \tfrac{1}{2}\rho_a C_d W^2 R^2(\tfrac{1}{2}\pi - \alpha - \sin\alpha\cos\alpha),$$

where $\alpha = \sin^{-1}(z_o/R)$. The vertical distance to the centroid is

$$z = 2R\cos^3\alpha/3(\tfrac{1}{2}\pi - \alpha - \sin\alpha\cos\alpha).$$

Note that when $z_o = 0$, the above expressions for the buoyancy force and centroidal distance reduce to those for a hemisphere.

For the support *mast*, only the component of the flow perpendicular to the mast contributes to the moment generating drag. Hence $U(\xi) = W\cos\theta$, and the loading function is integrated with respect to ξ. The projected frontal area is that of a rectangle of height $H = \xi_2 - \xi_1$ and width $2R$, where R is the radius of the mast. Hence, $S(\xi) = 2R =$ constant. The total drag force on the mast is therefore

$$F_d = \tfrac{1}{2}\rho_a C_d (W\cos\theta)^2 (2RH).$$

The centroidal distance is

$$\zeta = (\xi_2 + \xi_1)/2.$$

For the *antenna*, the wind loading function $U(\xi) = W\cos\theta$. The projected frontal area is that of a regular trapezoid of height $H = \xi_3 - \xi_2$ and bases $2R_2$ and $2R_3$, where R_2 and R_3 are the radii of the bottom and top of the antenna, respectively. Hence, $S(\xi) = 2(a\xi \;\; b)$, where $a = (R_3 - R_2)/H$ and $b = R_2 - a\xi_2$. The total drag force on the antenna is

$$F_d = \tfrac{1}{2}\rho_a C_D (W\cos\theta)^2 (R_3 + R_2)H.$$

The centroidal distance is

$$\zeta = [(2R_3 + R_2)\xi_3 + (R_3 + 2R_2)\xi_2]/3(R_3 + R_2)$$

Note that when $R_3 = R_2$, the above expressions reduce to those for a cylinder.

D3.2.2 Wave Loads. The wave loading function is distributed over five regions: the lower part of the float, the electronics/battery canister, the pendulous arm, the cable, and the ballast weight. Since the cable and ballast weight subsystem can pivot at the end of the pendulous arm, it will not (in general) be collinear with the buoy axis. As with the case of wind loading, any flow interference effects are neglected and the drag coefficient must be determined separately in each region.

For the *float*, the flow component $U(z) = V(z) = A\omega e^{kz}$, the design wave profile. The projected frontal area is that of a segment of a circle of radius R, and as before, $S(z) = 2(R^2 - z^2)^{1/2}$. The total drag force on the submerged portion of the float is

$$F_d = \tfrac{1}{2}\rho_w C_d \int_{-R}^{z_o} {-R}\,(A\omega e^{kz})^2\, 2(R^2 - z^2)^{1/2}\, dz.$$

In order to evaluate the integral, a further assumption is made: since the design wave profile is nearly constant over the lower float, let $V(z) = V(0) = A\omega$. Then the total drag force is

$$F_d = \tfrac{1}{2}\rho_w C_d (A\omega)^2 R^2(\tfrac{1}{2}\pi + \alpha + \sin\alpha\cos\alpha),$$

where $\alpha = \sin^{-1} z_o/R)$. The vertical distance to the centroid is

$$\overline{z} = -2R\cos^3\alpha/3(\tfrac{1}{2}\pi + \alpha + \sin\alpha\cos\alpha).$$

For the *canister,* the flow component $U(\xi) = V(z)\cos\theta \approx A\omega\cos\theta\, e^{k\xi}$ for small angles θ. The projected frontal area is that of a rectangle of height $H = \xi_1 - \xi_2$ and width 2R, where R is the radius of the canister; hence, $S(\xi)\, 2R =$ constant. The total drag force on the canister is therefore

$$F_d = \tfrac{1}{2}\rho_w C_d (A\omega\cos\theta)^2\, R(e^{2k\xi} - e^{2k\xi_2})/k.$$

The centroidal distance is

$$\zeta = \frac{\xi_1 e^{2k\xi_1} - \xi_2 e^{2k\xi_2}}{e^{2k\xi_1} - e^{2k\xi_{32}}} - \frac{1}{2k}$$

For the *pendulous arm,* the projected frontal area is that of a rectangle of height $H = \xi_2 - \xi_3$ and width 2R, where R is the radius of the arm. The expressions for the drag force and centroidal distance are the same as for the canister above except the respective coordinate distances are ξ_2 and ξ_3 for the top and bottom of the arm.

For the *cable* (oriented along the direction ξ' at an angle ϕ to the vertical), the flow component perpendicular to the cable is $U(\xi') = V(z)\cos\phi \approx A\omega\cos\phi\, e^{k\xi'}$. The projected frontal area is that of a rectangle of height H and width 2R, where R is the radius of the cable. Hence $S(\xi') = 2R$. In terms of the distance ξ_3 (the distance from the center of the float to the end of the pendulous arm), the total drag force on the cable is

$$F_d = \tfrac{1}{2}\rho_w C_d (A\omega\cos\phi)^2\, R\, e^{2k\xi_3}(1 - e^{-2kH})/k$$

The distance from the end of the pendulous arm to the force centroid of the cable is

$$\zeta' = [H\, e^{-2kH}/(1 - e^{-2kH})] - [\tfrac{1}{2}k].$$

For the *ballast weight,* the flow component is $U(z) \approx A\omega\, e^{kz_4}$, where $z_4 = \xi_3\cos\theta - H\cos\phi$ is the (vertical) depth of the ballast weight. Here ξ_3 is the distance from the center of the float to the end of the pendulous arm and H is the length of the cable. The projected frontal area to the flow is that of a circle of radius R, and $S(z) = 2(R^2 - z^2)^{1/2}$. In terms of the distance ξ_3, the total drag force on the ballast weight is

$$F_d \approx \tfrac{1}{2}\rho_w C_d (A\omega)^2\, \pi R^2\, e^{2k\xi_3}\, e^{-2kH}.$$

The force centroid is at the center of the ballast weight, located at a vertical depth of $z = H\cos\phi$ below the end of the pendulous arm.

D3.3 Moments

The moment of a force represents the tendency of that force to rotate the body on which it acts about an axis perpendicular to the plane containing the force (force plane). The magnitude of the moment, M, is given by $F \cdot r$, where F is the magnitude of the force, and r (the moment arm) is the perpendicular distance from the line-of-action of the force to the axis of rotation. By convention, moments imparting a counterclockwise rotation are considered positive, those imparting a clockwise rotation negative.

For the representative buoy, the net moment about the center of the float is the sum of all moments due to wind and wave loads, buoyancy forces, and the weight of the system components. For the system to be in equilibrium, this net moment must equal zero. This condition allows for the determination of the maximum tilt of the system under specified environmental conditions.

Since the cable is not necessarily collinear with the buoy axis, the resolution of forces is considered separately for two subsystems: the antenna/mast/float/canister/pendulous arm, and the cable/ballast weight. The net moment about the end of the pendulous arm due to the forces acting on the cable and ballast weight is first computed in order to determine the tilt angle, ϕ, of the cable from the vertical. The net moment about the center of the float due to the forces acting on the antenna, mast, float, canister, and pendulous arm, and including the resultant force of the cable/ballast weight subsystem, is finally computed in order to determine the tilt angle, θ, of the buoy axis from the vertical.

D3.3.3 Moments due to Body Forces. The resultant weight and buoyancy forces for each buoy component act vertically through their respective centroids. For the *antenna, mast, canister,* and *pendulous arm,* the moment arm is therefore given by $r = \zeta \sin\theta$, where ζ is the centroidal distance along the buoy axis and θ is the tilt angle of the buoy axis from vertical. The moments due to the weight and buoyancy are, respectively,

$$M_w = F_w \zeta_w \sin\theta \text{ and } M_b = F_b \zeta_b \sin\theta.$$

For the *float,* the mass and buoyancy centroids lie on the vertical passing through the center of rotation. Hence the respective moment arms and moments are zero. For the neutrally buoyant *cable,* the net body force is zero and therefore the net moment is zero. For the *ballast weight,* the moment arm for rotation about the end of the pendulous arm is H $\sin\phi$, where H is the length of the cable between the end of the pendulous arm and the ballast weight, and $\hat{\phi}$ is the tilt angle of the cable from vertical. The moments about the end of the pendulous arm due to the weight and buoyancy are, respectively,

$$M_w = F_w H \sin\phi \text{ and } M_b = F_b H \sin\phi.$$

Obviously, when the buoy is upright, $\theta = \phi = 0$ and all body forces act through the center of rotation of the system, thus producing no moments.

D3.3.2 Moments due to Loading Forces. For the *antenna, mast, canister,* and *pendulous arm,* the resulting drag forces are perpendicular to the buoy axis at their respective force centroids. Hence the moment arms are simply the centroidal distances ζ. The moments due to the drag force are

$$M_d = F_d \zeta.$$

For the *float,* the resultant wind and wave loads are perpendicular to the vertical; hence the moment arms are the vertical centroidal distance $\bar{z}$. The moments are

$$M_d = F_d \bar{z}.$$

For the *cable,* the moment arm is equal to the distance from the end of the pendulous arm to the force centroid, ζ'. The moment about the end of the pendulous arm is therefore

$$M_d = F_d \zeta'.$$

For the *ballast weight,* the resultant wave load is perpendicular to the vertical; hence the moment arm is $H \cos\phi$, where H is the length of the cable. The moment about the end of the pendulous arm is therefore

$$M_d = F_d H \cos\phi.$$

D4. PREFERRED BUOY STABILITY EVALUATIONS

In the following subsections, the tilt of the preferred buoy designs is estimated for typical Static sea state 6 conditions. Complicated structures are approximated by aerodynamic or hydrodynamic equivalent simple shapes, such as cylinders, spheres, etc. Known values for weights, centers of gravity (mass centroids), drag forces, etc., are used when available.

D4.1 Combination Master/Slave Station

The Combination Master/Slave Station buoy consists of

(a) an antenna (modeled as a truncated cone of height = 15 feet and base radii = 0.6 and 1.5 inches);

(b) a mast assembly including air vents, navigation lights, etc. (modeled as a cylinder of height = 45.4 inches and radius = 12 inches);

(c) a flotation sphere which also houses system electronics (radius = 29 inches; equivalent aero/hydrodynamic radius = 30 inches);

(d) a battery canister (modeled as a cylinder of height = 31 inches and radius = 14.5 inches; equivalent hydrodynamic radius = 15 inches);

(e) a hollow pendulous arm (modeled as a cylinder of height = 8 feet and radius = 2 inches);

(f) a cable (modeled as an elongated cylinder of length = 39.5 feet and radius = 0.25 inch);

(g) a ballast weight (modeled as a sphere of radius = 7 inches; equivalent hydrodynamic radius = 7.5 inches).

This station is identical to the representative buoy with the exception that the masses of component parts are not necessarily distributed uniformly. As with the representative buoy, the cable is assumed neutrally buoyant so that the net moment on the cable due to its weight and buoyancy is zero. The ballast weight is that necessary for the waterline to coincide with the center of the flotation sphere (i.e., $z_0 = 0$). The estimated or computed weights, buoyancies, and drag forces for each of the station components, along with the corresponding moments, are summarized in table D-2.

Table D-2. Forces (lb) and moments (ft-lb) for the Combination Master/Slave Station buoy.

	WEIGHT		BUOYANCY		DRAG	
	F_w	M_w	F_b	M_b	F_d	M_d
Antenna	25.0	+325.0a			$6.7b^2$	$+84.4b^2$
Mast	30.0	+156.0a			$2.9b^2$	$+12.5b^2$
Sphere	1000.0	0.				
(upper)					3.7	+4.0
(lower)			1894.2	0.	92.2	+97.7
Canister	900.0	−2880.0a	763.0	+2830.8a	$50.3b^2$	$+184.6b^2$
Arm	51.0	−459.0a	7.0	+63.0a	$68.3b^2$	$+591.7b^2$
Cable					$13.5d^2$	$+164.3d^2$
Ballast	711.5	−28458.4c	53.3	+2131.2c	1.0	+38.8d

Note: $a = \sin\theta$, $b = \cos\theta$, $c = \sin\phi$, $d = \cos\phi$

The sum of the moments about the end of the pendulous arm due to forces acting on the cable and ballast weight is

$$-26327.2 \sin\phi + 164.3 \cos^2\phi + 38.8 \cos\phi.$$

For equilibrium conditions, this sum must equal zero. Solving the resulting equation for ϕ, the tilt of the cable is $\phi = 0.4°$. Therefore, the horizontal and vertical components of the net force acting on the end of the pendulous arm due to the cable and ballast weight are, respectively,

$$(13.5 \cos^2\phi) \cos\phi + 1.0 = 14.5 \quad \text{and} \quad (13.5 \cos^2\phi) \sin\phi - 658.2 = -658.1.$$

These component forces produce moments about the center of the flotation sphere of, respectively,

$$14.5\,(13 \cos\theta) = 188.5 \cos\theta \quad \text{and} \quad -658.1\,(13 \sin\theta) = -8555.3 \sin\theta.$$

The sum of the moments about the center of the flotation sphere, including the net moment due to the forces acting on the cable and ballast weight, is

$$-8519.5 \sin\theta + 873.2 \cos^2\theta + 188.5 \cos\theta + 101.7.$$

For the system to be in equilibrium, this sum must equal zero. Thus, solving for θ, the tilt of the station is $\theta = 7.7°$ from vertical. This represents a "worst-case" situation.

D4.2 Master Station with Horizontally-Polarized Antenna

The Master Station with horizontally-polarized antenna consists of

(a) a pair of mutually perpendicular horizontal antennas (each radial arm modeled as a truncated cone of length = 5 feet and base radii = 0.5 and 0.25 inches);

(b) a self-erecting support tower (height = 26 feet);

(c) a pivoting frame (modeled as dual parallel cylinders of radius = 3 inches, each extending 12 feet above and below their common axle);

(d) a flotation hull (modeled as a horizontal cylinder of length = 25 feet and radius = 2 feet);

(e) a cable (modeled as an elongated cylinder of length = 70 feet and radius = 0.6 inches);

(f) a ballast weight (modeled as a sphere of radius = 0.75 feet).

The antenna pair for this station are supported by a self-erecting tower and pivoting frame at a nominal elevation of 40 feet above sea level. The antenna pair are modeled with one antenna perpendicular to the wind and the other into the wind at an angle of attack, ϕ, determined by the tilt of the vertical axis of the station. The component of the wind perpendicular to this latter antenna is thus W $\sin\phi$ but, since the resultant force acts on a line passing through the center of rotation, no moment is produced. The frame, which extends vertically on either side of the flotation hull, pivots about a transverse axle mounted to the top of the hull in order to decouple the antenna/tower/frame from the pitching motions of the hull. Roll stability is maintained in a manner similar to the representative buoy where the lower extensions of the frame act as a pendulous arm. The loading forces are assumed to be perpendicular to the longitudinal axis (roll axis) of the flotation hull, thus maximizing rolling tendencies ("worst-case"). In this configuration the dual cylinders of the pivoting frame are aligned fore and aft of each other with respect to the direction of the flow, and drag interference on the after cylinder must be considered. The cable is assumed neutrally buoyant and the ballast weight is that necessary for the waterline to coincide with the centerline of the flotation hull (i.e., $z_0 = 0$). The estimated or computed weights, buoyancies, and drag forces for the station components, along with their corresponding moments, are summarized in table D.3.

Table D.3. Forces (lb) and moments (ft-lb) for the Master Station with horizontally-polarized antenna.

	WEIGHT		BUOYANCY		DRAG	
	F_w	M_w	F_b	M_b	F_d	M_d
Antenna	4.0	+160.0a			1.6	+63.6b
Tower	200.0	+5400.0a			7.0	+189.0
Hull	8200.0	0.				
(upper)					26.5	+26.5
(lower)			10065.4	0.	573.0	+561.6
Frame	400.0	−800.0a				
(upper)					$15.8b^2$	$+126.2b^2$
(lower)			23.0	+115.0a	$160.4b^2$	$+907.8b^2$
Cable					$42.1d^2$	$+623.6d^2$
Ballast	1397.6	−97831.3c	113.2	+7926.8c	0.3	+17.5d

Note: $a = \sin\theta$, $b = \cos\theta$, $c = \sin\phi$, $d = \cos\phi$

The sum of the moments about the bottom of the pivoting frame due to forces acting on the cable and ballast weight is

$$-89904.5 \sin\phi + 623.6 \cos^2\phi + 17.5 \cos\phi.$$

For equilibrium conditions, this sum must equal zero. Solving the resulting equation for ϕ, the tilt of the cable is $\phi = 0.4°$. Therefore, the horizontal and vertical components of the net force acting on the bottom of the pivoting frame due to the cable and ballast weight are, respectively

$$(42.1 \cos^2\phi) \cos\phi + 0.3 = 42.4 \text{ and } (42.1 \cos^2\phi) \sin\phi - 1284.4 = -1284.1.$$

These component forces produce moments about the roll axis of the flotation hull of, respectively,

$$42.4\ (10 \cos\theta) = 424 \cos\theta \text{ and } -1284.1\ (10 \sin\theta) = -12841 \sin\theta.$$

The sum of the moments about the roll axis of the flotation hull, including net moment due to the forces acting on the cable and ballast weight, is

$$-7966.0 \sin\theta + 1034.0 \cos^2\theta + 487.6 \cos\theta + 777.1.$$

For the system to be in equilibrium, this sum must equal zero. Thus, solving for θ, the maximum roll of the station is $\theta = 16.0°$ from vertical. This angle is greater than the design criterion of 10°. However, if the station is drogue-moored or anchored, the flotation hull will tend to align with the direction of the wave loading; hence wave loads in the transverse plane (roll plane) will be minimized. If all wave loads are neglected, the net moment about the bottom of the pivoting frame due to body forces acting on the cable and ballast weight is $-89904.5 \sin\phi$; hence $\phi = 0$. The moment about the roll axis of the flotation hull due to the body forces acting on the cable and ballast weight is

$$-1284.4(10 \sin\theta) = -12844 \sin\theta.$$

The net moment about the roll axis of the flotation hull thus becomes

$$-7969.0 \sin\theta = 126.2 \cos^2\theta + 63.6 \cos\theta + 215.5.$$

Equating to zero and solving for θ, the roll under equilibrium conditions becomes 2.9° from vertical.

D4.3 Covert Station which Rarely Transmits

The Covert Station which rarely transmits is a small, air-deployable station that consists of

(a) an antenna (modeled as a truncated cone of height = 176 inches and base radii = 5/8 and 1/8 inches);

(b) a canister (modeled as a cylinder of height = 4 feet and radius = 4 inches);

(c) an inflatable flotation collar (modeled as a sphere of radius = 1 foot centered 16 inches below the top of the canister);

(d) a four-line bridle suspended from hinged arms extending radially outward 15 inches from the buoy axis and forming a vertex 7 feet below the center of the flotation collar (each line modeled as an elongated cylinder of length = 54.12 inches and radius = 1/16 inch);

(e) a cable (modeled as an elongated cylinder of height = 23 feet and radius = 1/8 inch);

(f) a ballast weight (modeled as a cylinder of height = 9 inches and radius = 4 inches).

This station is identical to the representative buoy except that the four-line bridle takes the place of the pendulous arm of the representative buoy. For small angles of tilt (< 16.1°), tension is supplied to all four lines but for larger angles, one or more of the bridal lines will lie slack. For simplicity, the four lines are each modeled as if they were parallel to the axis of the station. The bridle lines and cable are assumed neutrally buoyant, and the ballast weight (modeled as a cylinder rather than a sphere) is that necessary for the waterline to coincide with the center of the flotation collar (i.e., $z_0 = 0$). The estimated or computed weights, buoyancies, and drag forces for the station components, along with their corresponding moments, are summarized in table D.4.

Table D.4. Forces (lb) and moments (ft-lb) for the Covert Station which rarely transmits.

	WEIGHT		BUOYANCY		DRAG	
	F_w	M_w	F_b	M_b	F_d	M_d
Antenna	9.0	57.0			$2.1b^2$	$15.1b^2$
Collar	4.0	0.				
(upper)					0.3	0.1
(lower)			134.2	0.	11.8	5.0
Canister	108.5	−126.9a				
(upper)					$0.3b^2$	$0.4b^2$
(lower)			37.3	68.2a	$25.1b^2$	$45.6b^2$
Bridle					$6.2b^2$	$29.5b^2$
Cable					$8.3d^2$	$72.7d^2$
Ballast	66.8	−1535.9c	16.8	385.9c	2.5	57.0d

Note: $a = \sin\theta$, $b = \cos\theta$, $c = \sin\phi$, $d = \cos\phi$

The sum of the moments about the lower end of the bridle due to forces acting on the cable and ballast weight is

$$-1150.5 \sin\phi + 72.2 \cos^2\phi + 57.0 \cos\phi.$$

For equilibrium conditions, this sum must equal zero. Solving the resulting equation for ϕ, the tilt of the cable is $\hat{\phi} = 6.4°$. Therefore, the horizontal and vertical components of the net force acting on the end of the bridle due to the cable and ballast weight are, respectively

$$(8.3 \cos^2\phi) \cos\phi + 2.5 = 10.7 \quad \text{and} \quad (8.3 \cos^2\phi) \sin\phi - 50.0 = -49.1.$$

These component forces produce moments about the center of the flotation collar of, respectively,

$$10.7 (7 \cos\theta) = 74.9 \cos\theta \quad \text{and} \quad -49.1 (7 \sin\theta) = 1343.7 \sin\theta.$$

The sum of the moments about the center of the flotation collar, including the net moment due to the forces acting on the cable and ballast weight, is

$$-345.4 \sin\theta + 90.6 \cos^2\theta + 74.9 \cos\theta + 5.1.$$

For the system to be in equilibrium, this sum must equal zero. Thus, solving for θ, the tilt of the station is $\theta = 25.2°$ from vertical. This angle, which exceeds the design criterion of 10°, is due largely to the small size of the station; the reserve buoyancy is insufficient to support a large enough ballast weight to supply the necessary righting moment to maintain the vertical stability of the station.